ASSESSMENT OF WATER RESOURCES IN A HUMID WATERSHED AND A SEMI-ARID WATERSHED; NECHES RIVER BASIN, TX AND CANADIAN RIVER BASIN, NM

A Dissertation

by

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ABSTRACT

Water is the most important resource on Earth. Climate and land cover changes are two important factors that directly influenced water resources. This research provides important information for water resources management and contributes on understanding of the responses of water resources to climate and land cover changes in two different climates.

The Neches River watershed located in a humid subtropical climate had a 0.7 °C increase in temperature and a 16.3 % increase in precipitation. Developed and crop land covers increased whereas vegetation cover decreased, as a result of human activities. Hydrologic responses to climate and land cover changes resulted in the increases of surface runoff (15.0 %), soil water content (2.7 %), evapotranspiration (20.1 %), and a decrease of groundwater discharge (9.2 %). Surface runoff had an increasing trend with precipitation whereas soil water content was sensitive to changes in land cover, especially human intervention.

The Canadian River watershed, a semi-arid watershed, experienced a 0.9 °C increase in temperature and a 10.9 % decrease in precipitation. Land cover was converted from developed and crop lands into barren land and grass covers, as a result of the decrease in human activity. The change of grass and forest covers into bush/shrub cover is thought to be linked to climate change. Surface runoff, groundwater discharge, soil water content, and evapotranspiration were all decreased by 10.2 %, 10.0 %, 7.7 %,

and 9.4%, respectively. Hydrologic parameters generally follow similar patterns to that of precipitation.

The trend in water resources followed a similar trend of precipitation for the two watersheds with different climates; a humid watershed and a semi-arid watershed. The humid climate watershed, the Neches River watershed, experienced increasing trends in temperature and precipitation. Groundwater discharge was sensitive to changes in land cover caused by human activities. The semi-arid watershed, the Canadian River watershed, had an increase in precipitation and a decrease in precipitation. Conversion of developed and crop land covers into barren and grass land covers was thought to be the result of the decrease in human activity. The volume of soil water was relatively offset by a combination of precipitation changes and land-cover changes.

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1. INTRODUCTION

1.1 Introduction and Problem Statement

Climate change is a global phenomenon. This phenomenon is receiving broad-based discussion in the science community, as well as in the international press (USGCRP, 2009; Nemeckova et al., 2011; Zeng et al., 2012). Much of this discussion focuses on the potential impact of climate change on water resources (IPCC, 2007; Charlton and Arnell, 2011). It appears that climate change is used as a synonym for global warming (Mohseni and Stefan, 2001; USGCRP, 2009; Liu and Xia, 2011). Because of this use, it seems much of the research is focusing on the causes and potential results of global warming (Arnell and Reynard, 1996; Peel et al., 2010; Liu and Xia, 2011).

Climate is defined as the average weather conditions of a given area or region over 35 year period. The weather condition includes the temperature, precipitation, and wind (Gruza and Rankova, 2004; UGSCRP, 2009). Thus, when one refers to climate change one is telling about the long-term impact of change.

Climate change does not mean that all locations on Earth show the same pattern of change (Gerstengarbe and Werner, 2009; USGCRP 2009; Crosbie et al., 2012). To understand the long-term spatial distribution of temperatures and precipitation, one has to realize that climate change is driven by the variability of atmospheric processes. These processes are considered to be responsible for increased temperature and precipitation in some areas, whereas hotter temperature and reduced precipitation will concurrently occur in other regions. Either increased temperature / precipitation or hotter temperature / decreased precipitation will dramatically impact the water resources of a region. Thus, it is assumed that different types of climates will respond differently to the long-term impact of climate change on water resources of a given region (IPCC, 2007; Zhang et al., 2008; USGCRP, 2009; Crosbie et al., 2012).

The climate of Earth has been categorized into five distinct categories (Koppen-Geeiger climate classification) and Texas ranges from sub-humid to semi-arid. One has to ask what the impact of climate change is on these two distinct climatic regions in Texas? And, further what would be the long-term impact on the water resources in each of these specific climatic region? Because of my interest in the impact of climate change on water resources in the southeast, these focused on two drainage basins, which have distinct, separate climates. I selected the Neches River Basin in East Texas, as representative of a sub-humid climate, and the Canadian River Basin in eastern New Mexico, as representative of a semi-arid climate.

It has been suggested that humid subtropical climates have experienced increasing patterns of temperature by 1~2 °C and precipitation by 10~15 % during the last 50 years (Neff et al., 2000; Limaye et al., 2001; Nobrega et al., 2011; Candela et al., 2012; Sun et al., 2012). Such changes in the climate could result in significant impact on the timing and amount of extreme hydrological events, such as floods (Middelkoop et al., 2001; IPCC, 2007; USGCRP 2009). The humid subtropical climate accounts for 16 % of the world in terms of land mass area, and a considerable amount of population of the world resides in this climate zone, including east Texas and Houston (Fraedrich et al., 2001; Peel et al., 2007; Crosbie et al., 2012).

On the other hand, a semi-arid climate has shown a 1.5~2.5 °C increase in temperature and a 5~10 % decrease in precipitation over the last 15 to 50 years (Ragab and Prubhomme, 2002; Favreau et al., 2009; Tefera, 2011; Wang et al., 2011). The semi-arid climate experiences frequent droughts and the water resources are regarded as the single most important factor in controlling ecosystem processes because of the dry environments (IPCC, 2007; Liping et al., 2012). The semi-arid climate accounts for 32 % of the land area in the world, which is the largest climate zone and includes west Texas and New Mexico (Fraedrich et al., 2001; Peel et al., 2007; Kim et al., 2008; Crosbie et al., 2012). Thus, understanding natural responses, including water resources regarding changes in temperature and precipitation, will contribute significantly for ecosystem management and human survival in the two different types of climates because of their agricultural and demographic importance.

The states of Texas and New Mexico extend over a large geographic region and include over various types of climate systems. The climate ranges from humid subtropical in the southeastern regions of Texas to semi-arid areas of New Mexico. As the states are highly dependent on water resources for irrigation, drinking water, and municipal uses, the sustainability of water resources in Texas and New Mexico has received recent attention (USGCRP, 2009; Xu and Yang, 2012). Thus, as a result of the different types of climates in Texas and New Mexico, one begins to question how the water resources in the two climatic types response to climate change. This leads one to develop the dissertation research question: What will be the impact of changes in temperature and precipitation on the water resources in a humid subtropical climate as compared to a semi-arid climate?

1.2 Goal of the Dissertation

Because the climate systems of Texas and New Mexico are diverse, no single model can explain the impact of changes in temperature and precipitation on the water resources (Peel et al., 2007; Tummuri and Loucks, 2012). Various researchers have suggested that changes in temperature and precipitation will impact water resources differently (IPCC 2007; Zhang et al., 2008; USGCRP, 2009; Liu et al., 2011; Sun et al., 2012). Thus, to gain an understanding of the responses in two different types of climates in Texas and New Mexico with regards to changes in temperature and precipitation, this dissertation focuses on the responses of two climate systems; a humid subtropical climate and a semi-arid climate. The research foci of the dissertation is to investigate temporal changes in water resources with regard to changes in temperature and precipitation during a 40 year period from 1970 to 2009 for a humid subtropical watershed in Texas and a semi-arid watershed in New Mexico.

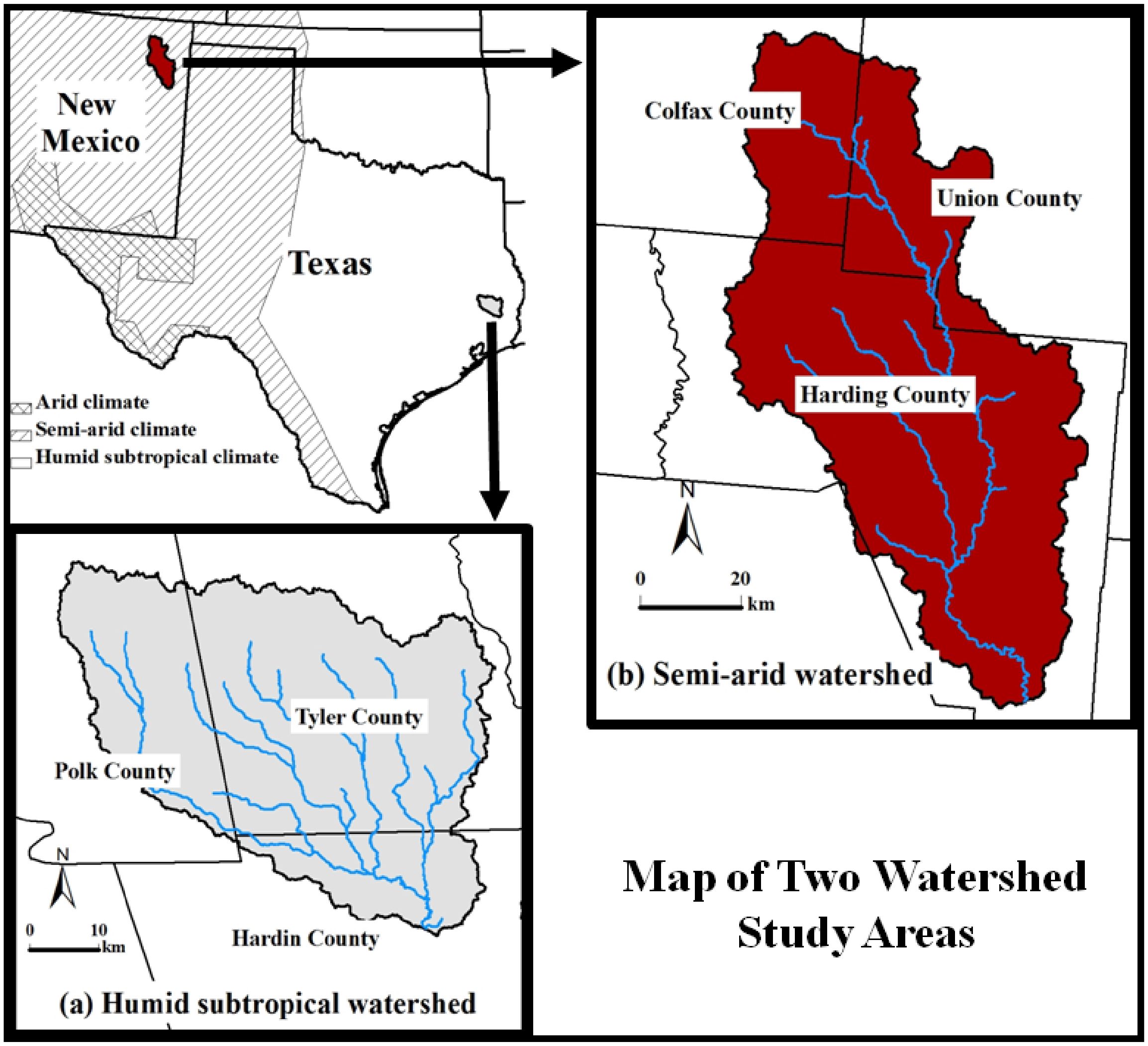

Figure 1.1. Location map of the two study areas; (a) Humid subtropical watershed and (b) Semi-arid watershed (http://koeppen-geiger.vu-wien.ac.at/present.htm).

1.3 The Two Drainage Basins

The humid subtropical watershed consists of a part of the Neches River Basin, southeastern Texas (Figure 1.1(a)). It has a total area of 2,221 km^2 and extends into Polk, Tyler, and Hardin counties in Texas. The typical climate is represented by the annual total precipitation of 1,422.1 mm and an annual mean temperature 19.1 °C based on the

1970-2009 data in the study area (Southern Regional Climate Center, 2010). The land cover in the study area consists mostly of vegetation, water, and barren land with minimal human activities.

On the other hand, the semi-arid watershed is located in northeastern New Mexico (Figure 1.1(b)). It has an area of 5,289.9 km^2, and is a part of the Upper Canadian River Basin. This study area exists in Harding, Union, and Colfax counties in New Mexico. The annual mean temperature is 11.3 °C and the annual total precipitation is 398.3 mm; these were recorded from 1970 to 2009 for the study area (Western Regional Climate Center, 2010). The land cover in the study area consists mainly of grass land, bush/shrub land, forest and barren land. Because of an extremely low population density, human intervention is minimal and can be ignored.

These two study areas have long records of weather data with relatively dense meteorological and hydrological observation networks from 1970 to 2009. Because of undeveloped land-cover characteristics, the study areas are optimal to study the impact of changes in temperature and precipitation on water resources in which human impacts are minimal. In this research, I have tested two hypotheses which are very important in understanding the impact of changes in temperature and precipitation on water resources in a humid subtropical watershed and a semi-arid watershed. The first hypothesis is: the different types of climates can respond differently to the impact of changes in temperature and precipitation on water resources. The second hypothesis is that the impact of changes in temperature and precipitation on water resources can show a different magnitude of changes in the water resources where human impacts are minimal compared to other locations.

1.4 Objectives

Water resources of a region are impacted by various physical parameters. Among these are: atmospheric processes, vegetation characteristics, geomorphic processes, surface water, groundwater, and human activities. The impact of these parameters have been considered separately by various researchers (Goudie, 2006; Charlton and Arnell, 2011; Nemecko et al., 2011; Zeng et al., 2012). In this dissertation, the role of changes in temperature and precipitation along with changes in land cover will be the primary parameters considered with regard to the natural responses in water resources.

The objectives of the dissertation are:

- Evaluate the changes of temperature and precipitation in two watersheds with different climates;
- Identify the changes of land cover in two watersheds with different climates;
- Simulate the changes of water resources in two different watersheds using the Soil and Water Assessment Tool (SWAT); and
- Investigate the linkage between water resources and changes in temperature, precipitation and land cover in two different watersheds

1.5 Organization of the Dissertation

This dissertation consists of a general introduction (Chapter 1), two research papers (Chapter 2 and 3), and overall conclusions (Chapter 4). The specifics of each chapter are described in the following paragraphs.

Chapter 1 contains the research background and objectives of the dissertation.

Chapter 2 provides the impact of changes in temperature and precipitation on water resources in a watershed with a humid subtropical climate using data from 1970 to 2009. This chapter models an interconnected system of climate, land cover, and water resources in a humid subtropical watershed based on three different SWAT simulations. The hydrologic responses related to changes in temperature and precipitation are discussed. The chapter further characterizes relative to water resources the relationship between each parameter of the hydrologic cycle for a humid subtropical watershed.

Chapter 3 examines the impacts of changes in temperature and precipitation on water resources in a semi-arid watershed using the data from 1970 to 2009. This chapter quantifies land cover changes in a semi-arid watershed, based on historical land cover maps. The responses of water resources to changes in temperature and precipitation are discussed. The chapter also examines the contribution of precipitation to other hydrologic parameters.

Lastly, Chapter 4 presents an overall of major findings, conclusions, and implications of the dissertation.

2. A HUMID SUBTROPICAL WATERSHED

2.1 Introduction

Water is the most important element for life on Earth. It is used for many purposes including power generation, industry, public water supply, and agriculture. In addition, water plays a fundamental role in the interaction between ecological and economical processes (Long et al., 2007; Barron et al., 2012). It has been reported that water resources are becoming increasingly important because of climate change, land cover change, population growth and increasing economic development (IPCC, 2007; USGCRP, 2009; Polebitski et al., 2011). As a result of these changes, many countries around the world face serious problems with their water supplies.

Climate change and land cover changes from human intervention are two important factors that directly influence water resources (Costa et al., 2008; Guo et al., 2008; Li et al., 2009; Ma et al., 2009; Wiley et al, 2010; Cuo et al., 2011). It is important to realize that climate change may influence significantly the hydrological cycle and may lead to a variety of water resources issues (Davies and Simonovic, 2005; Giambelluca, 2005; Liu and Xia, 2011). Climate change develops in response to the variation of precipitation and temperature, which impacts streamflow, runoff, and evapotranspiration all leading to alteration of the hydrological cycle (Li et al., 2009; Pang et al., 2012). On the other hand, land cover changes also can alter the regional hydrologic cycle by changing soil moisture, runoff, infiltration, evapotranspiration, and even precipitation (Goudie, 2006; Li et al., 2009; USGCRP, 2009; Xu et al., 2010).

Human activities also can have an impact on the hydrological cycle through the increase of developed land and creation of impervious surfaces, and decreases in vegetation cover and soil moisture. All of these leads to decreases in infiltration and increases in runoff, which can result in higher flood frequencies (Ma et al., 2009; Dixon and Earls, 2012). Therefore, we consider that climate change has a direct impact on global distribution of water resources whereas land cover change mainly controls local surface hydrological processes, which over a long term also can impact water resources.

Humid subtropical climates occupies 16 % of the land surface of the planet in terms of area and is mainly located in the southeastern part of North America, the southern parts of South America and eastern Asia, and the east coast of Australia (Fraedrich et al., 2001). Additionally, a significant amount of the population of the world resides in this climate zone. To illustrate, major cities such as Houston, Memphis, Atlanta, Hong Kong, and Buenos Aires, are located in humid subtropical areas (Peel et al., 2007). Fraedrich et al. (2001) showed that the area of humid climate increased by 2.5 % in North America and 6.0 % in Europe from 1951 to 2000. Kottek et al. (2006) concluded that the spatial distribution of humid climates will increase by the 2050s because of climate change. Thus, water resources in the humid climate zone are very important because of its spatial location, size and demographics. This fact highlights the importance of understanding the potential impact of climate change.

Many studies have been undertaken to assess the impacts of climate change on water resources in a humid subtropical climate (Limaye et al., 2001; IPCC, 2007; Nobrega et al., 2011; Candela et al., 2012; Sun et al. 2012). Fitzgerald and Walsh (1987) showed that the humid subtropical climate in the Severn Valley Basin, Australia, had a 15 % increase in precipitation and a 2 °C increase in temperature, which resulted in an increased runoff of 15 %. The humid subtropical climate of the southeastern US experienced an increase in precipitation by 10 % and a temperature increase of 1.5 °C, from 1966 to 1993. These changes have been linked to an increase in streamflow (Limaye et al., 2001).

This trend also appears to be occurring in humid climates. For example, Nobrega et al. (2011) showed that the humid climate in the south Brazil had a 10 % increase in precipitation, a 1 °C increase in temperature, and a 10 % increase in runoff from 1970 to 2001. Candela et al. (2012) concluded that precipitation increased 15 % and temperature increased 1.2 °C in the humid climate of northern Spain from 1984 to 2002. Increased streamflow and groundwater discharge has been linked to these changes.

As briefly mentioned previously, water resources can be affected by climate change and land cover changes. To clearly understand the impact of climate change solely on water resources, the impact of land-cover change caused by human impact has to be discounted (i.e., removed from a study). Although previous studies (Fitzgerald and Walsh, 1987; Limaye et al., 2001; Nobrega et al., 2011) have made advances understanding the impact of climate change on water resources in humid subtropical regions, no studies clearly focused on the impact of natural climate change (i.e., no anthropogenic intervention) on water resources in humid subtropical climate. Additionally, previous studies assessed the impact of climate change by generalizing one representative landcover for the relatively long-term observation period. Natural variations and human interventions in the landcover changes were not appropriately considered in the assessment. Thus, trying to defining the sole impact of climate change on water resources by discounting or ignoring land cover change is almost impossible. Nevertheless, my research uses watersheds with sparse human habitation and resulting stable land cover patterns to investigate the impact of changes in temperature and precipitation on water resources for a watershed basin in humid subtropical climate where human impact has been minimal and can be held as a constant during a 40-year period from 1970 to 2009. It is important to note that three land-cover types, representing sub-periods of the study period, are employed for the water resources assessment to obtain a more realistic estimation of impact. The impact of temperature and precipitation on water resources can be better defined with the most realistic hydrological model rather than simply observing one representative land-cover type.

2.2 Neches River Basin Study Area

The study area, with an area of 2,221 km^2, is located in southeastern Texas (Figure 2.1). It is a part of the Neches River Basin, which discharges into the Gulf of Mexico. It lies within Hydrologic Unit Code (HUC) 12020006 and extends into Polk, Tyler, and Hardin counties in Texas. The land cover of the study area consists mostly of vegetation, bare soil, and water. Because undeveloped land (excluding crop) accounted for over 95.8 % of the total area, the study area was selected to evaluate the impact of climate on water resources where human impact is minimal.

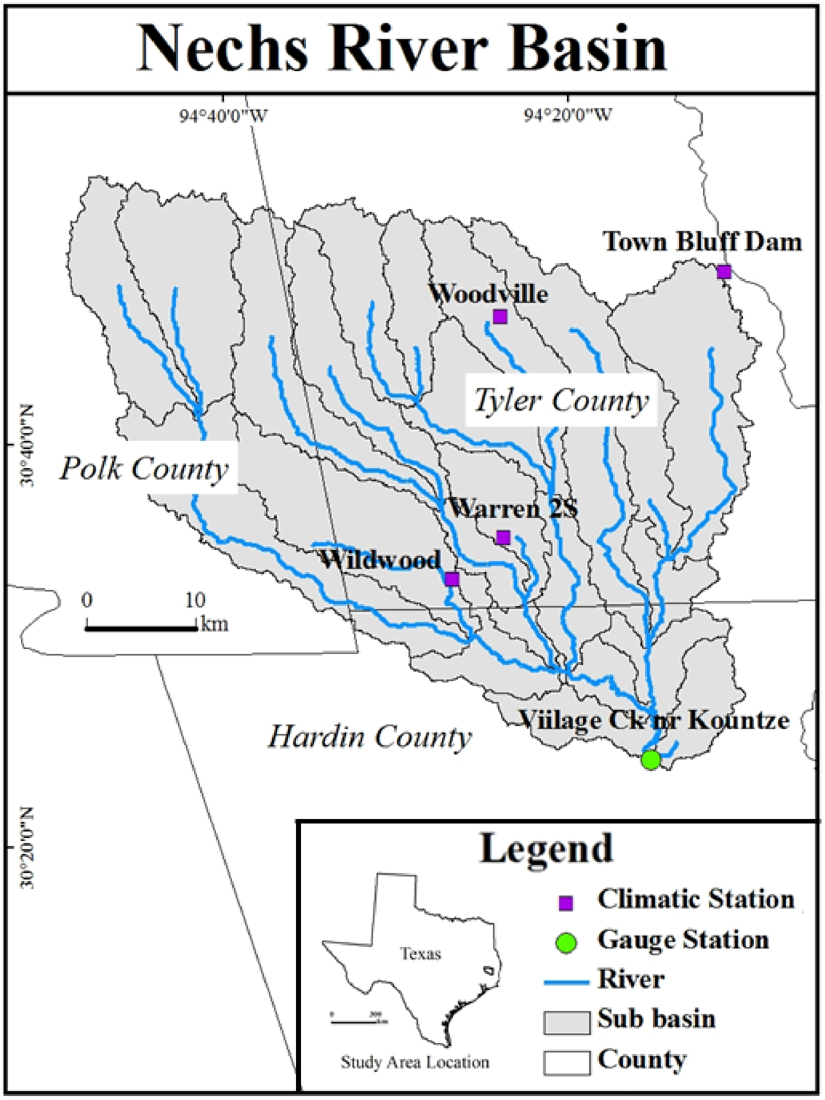

Figure 2.1. Location map of the study area with humid subtropical climate.

The climate of the study area is predominantly a humid subtropical climate with an annual mean temperature of 19.1 °C and an annual total precipitation of 1,422.1 mm, based on the 1970-2009 data of the four climatic stations; Town Bluff Dam, Warren 2S, Wildwood, and Woodville (Southern Regional Climate Center, 2010). The study area has four weather stations and one gauging station monitoring stream discharges (Figure 2.1). The study area provides a long period of weather data with a relatively dense meteorological and hydrological observation network. Because of its relatively undeveloped landcover characteristics and availability of quality weather data, the study area can be used to investigate the impact of temperature and precipitation on water resources in a humid subtropical climate, excluding human impact.

The objectives of this study are (1) to assess the changes in temperature and precipitation in a humid subtropical watershed during the period 1970 to 2009; (2) to identify the changes in land cover; and (3) to evaluate the impact of changes in temperature and precipitation on water resources in the study area. This research seeks to provide important information for water resources management and availability for a humid subtropical climate.

2.3 Materials and Methods

2.3.1 Data

Precipitation and temperature data were obtained from the National Climate Data Center (NCDC) of National Oceanic and Atmospheric Administration (NOAA) and United States Department of Agriculture (USDA). Daily temperature and precipitation data from 1970 to 2009 were used as the basic meteorological input data. The data represents the four weather stations within the watershed. During the forty years of observation, data for some periods are missing data because of irregular measurement at the NCDC sites. The periods with missing data were different for each weather station. The missing data does not cause a problem with the modeling software that was used in the study. For the occurrences of missing data from a weather station, the SWAT model automatically replaces the missing data from the SWAT library, which contains weather information for 1,041 stations around the US (SWAT 2009 User's Guide documentation).

Stream discharge data for the gauge station (08041500) was obtained from the National Water Information System (NWIS) of the US Geological Survey (USGS) (http://waterdata.usgs.gov/nwis). The continuous daily records of stream discharge data are available for the period 1970 to 2009. By aggregating continuous discharge measurements, daily average discharge was estimated and employed as the basic hydrological data input. This gauging station data were used for calibration of the SWAT models.

Table 2.1. Summary of weather and hydrological data used in this study.

Data type	Station ID	Acquisition period	Source	Location
Weather	Woodville (419898)	1970-2009	NOAA, USDA	Lat: 30.766692, Lon: -94.401711
	Warren 2 S (419480)	1970-2009	NOAA, USDA	Lat: 30.583358, Lon: -94.401707
	Town Bluff Dam (419101)	1970-2009	NOAA, USDA	Lat: 30.800447, Lon: -94.184125
	Wildwood (419754)	1970-2009	NOAA, USDA	Lat: 30.550024, Lon: -94.451706
Streamflow	Village Ck nr Kountze (8041500)	1970-2009	NWIS (USGS)	Lat: 30.397778, Lon: -94.263333

The State Soil Geographic database (STATSGO) was utilized also. The STATSGO is a digital soil map at 1:250,000 scale, which was created in 1994 by the Natural Resources Conservation Service (NRCS). STATSGO has been commonly used for local hydrologic modeling for county-level or smaller areas (Grassman et al., 2007; Geza and McCray, 2008). STATSGO data are used for calculating SWAT soil parameters, such as soil hydrologic group, layer thickness, bulk density, available water capacity, and soil texture.

A 30m-resolution Digital Elevation Model (DEM) was obtained from Earth Resource Observation and Sciences (EROS) of the USGS. The 30m DEM is employed in SWAT to build a stream network and to divide the watershed into subbasins. Elevation in the study area ranges from 30 m to 153 m with a mean watershed elevation of 64 m.

The land cover data sets were used to simulate three periods for the study area in the SWAT modes. I employed different land cover data representing different time periods: USGS Land Use and Land Cover (LULC) data, USGS National Land Cover Database (NLCD) 1992, and USGS NLCD 2001. The land cover data sets were classified based on the Anderson Land Cover Classification System (http://landcover.usgs.gov/usgslandcover.php), these data sets do not provide information on density of vegetation (http://landcover.usgs.gov/classes.php).

Land Use and Land Cover (LULC) data were completed via the manual interpretation of aerial photography from 1970s to 1980s (http://eros.usgs.gov/#/Find_Data). The data consist of nine land-cover categories and 37 sub-categories (http://water.usgs.gov/lookup/getgislist). The data had a spatial resolution of 400 meters; the accuracy of the land-cover classification was not reported by USGS. The data were based on 1: 250,000 scale USGS topographic maps. LULC also provides additional information on hydrologic units, county census numbers, and land ownership.

The National Land Cover Dataset (NLCD) 1992 was derived from early 1990s Landsat Thematic Mapper (TM) satellite data. The dataset is based on a 21 class land-cover classification system for the entire US. The spatial resolution for data is 30 m pixels. In addition to the land cover information, the dataset includes topography, agricultural statistics, soil properties, and census information. NLCD 1992 can be downloaded for each state from Earth Resource Observation and Science (EROS) USGS.

NLCD 2001 is based on Landsat Enhanced Thematic Mapper+ (ETM+) in the early 2000s. It is a 21 land-class land-cover classification system with a 30 m resolution. It was developed using a mapping zone with 65 zones covering the entire US and an additional 23 zones covering Alaska. The dataset contains standardized land-cover components, which are useful for a variety of potential applications. NLCD 2001 has been updated in version NLCD2006 using the Landsat ETM+. The 2006 dataset was generated by comparing spectral properties of Landsat imagery from 2001 to 2006.

2.3.2 SWAT model

The Soil and Water Assessment Tool (SWAT) is a basin-scale, continuous simulation model designed to estimate runoff, evapotranspiration, soil moisture, and groundwater discharge. SWAT was developed to simulate the impact of land use change in large, complex watersheds with varying soils, land covers, and management conditions over long periods of time. SWAT is a comprehensive watershed modeling tool that can simulate a number of water management processes in a watershed. SWAT has been used to describe and understand the processes operating in a watershed. SWAT has been chosen by the Environmental Protection Agency (EPA) as part of their Better Assessment Science Integrating point and Nonpoint Sources (BASINS) models (Grassman et al., 2007). SWAT is well known for its ability to simulate the hydrologic processes at the watershed scale (e.g., Grassman et al., 2007; Zhang et al., 2009).

The simulation developed with the SWAT model cannot be directly used to estimate the hydrologic processes at the watershed scale. The ability of the SWAT model must be evaluated through sensitivity analysis and calibration to sufficiently simulate the hydrologic processes in the study area (White and Chaubey, 2005).

Table 2.2. Eight SWAT parameters selected by a sensitivity analysis for this study.

No.	Parameters	Description	MIN	MAX
1	CN2	Runoff curve number	35	98
2	SOL_AWC	Soil available water capacity	0	1
3	ESCO	Soil evaporation compensation factor	0	1
4	ALPHA_BF	Baseflow alpha factor	0	1
5	GWQMN	Threshold depth of water in a shallow aquifer required for return flow to occur	0	5,000
6	CH_K2	Effective hydraulic conductivity in main channel	0	150
7	REVAPMN	Threshold depth of water in a shallow aquifer for re-evaporation to occur	0	1
8	GW_REVAP	Groundwater re-evaporation coefficient	0.02	0.2

MIN: Minimum, MAX: Maximum

Sensitivity analysis is the process for assessing the comparative change in a SWAT simulation resulting from a change in a SWAT parameter (Reungsang et al., 2005; Moriasi et al., 2007). A SWAT model includes a large number of parameters, which describe different hydrological conditions and characteristics across the watershed. The sensitivity analysis was conducted to find the most sensitive SWAT parameters associated with the study area. The sensitivity analysis provides parameter estimation guidance for the calibration step of the study area. Table 2.2 summarizes eight SWAT parameters selected for sensitivity analysis in this study.

Calibration is the process of estimating parameters by comparing the simulation with observed data in the SWAT model (Reungsang et al., 2005; Moriasi et al., 2007). The calibration is necessary because it is not possible to establish parameters by direct measurements. After the most sensitive parameters were identified in the sensitivity analysis, calibration was performed using the auto-calibration method, which is the external application of SWAT, to adjust these parameters within the permissible limits. Table 2.3 summarizes the three models of SWAT and the calibration values in the study.

Many statistical measures exist for the evaluation of hydrological models; Coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), Root Mean-Square Error (RMSE), and Percent Bias (PBIAS). The R^2 and NSE are the two most widely used statistics to evaluate the performance of the SWAT model (Muttiah and Wurbs, 2002; Daly, 2006; Moriasi et al., 2007; Mango et al., 2011; Perazzoli et al., 2012).

Coefficient of determination (R^2) shows the degree of collinearity between observed and simulated data. R^2 describes the proportion of the total variance in the observed data that can be explained the model. R^2 ranges from 0.0 to 1.0 with higher values indicating better performances. R^2 values greater than 0.5 are considered generally acceptable in hydrologic models (Moriasi et al., 2007). The R^2 is not sensitive, however, to high extreme values (outliers) and proportional differences between simulated and observed data (Daly, 2006).

The Nash-Sutcliffe Efficient (NSE) is a normalized statistic that determines the degree of the residual variance compared to the measured variance in hydrological models. It ranges from $-\infty$ to 1; a large NSE value denotes better model performance. Typically, NSE values, which are greater than 0.65, are considered good (Limaye et al., 2001; Moriasi et al., 2007; Li et al., 2009). NSE is recommended as the assessment tool for SWAT model performance by the American Society of Civil Engineers (Daly, 2006; Cho and Olivera, 2009).

Table 2.3. Summary for the three models of SWAT and the calibration values.

Simulations	Years	Land cover data	NSE	R^2
Period 1	1970-1989	LULC (1970s-1980s)	0.74	0.79
Period 2	1990-1999	NLCD 1992	0.66	0.67
Period 3	2000-2009	NLCD 2001	0.75	0.75

According to performance rating suggested by Moriasi et al. (2007), NSE values greater than 0.75 are very good and greater than 0.65 are good. The NSE values ranged from 0.66 to 0.75 in this study (Table 2.3), which indicates a good relationship between simulation and observed data. Also, the calibrated simulation and observed streamflow are plotted in Figure 2.2. It shows that there is a good agreement between the simulation and observed data in the study area.

For the current study, three SWAT models were constructed based on three simulation periods (period 1: 1970-1989, period 2: 1990-1999, and period 3: 2000-2009) with three land-cover data (period 1: LULC, period 2: NLCD 1992, and period 3: NLCD 2001), to simulate the most applicable and accurate hydrological model by applying land-cover data representing each period. As shown in Table 2.3, the land-cover data were used to present conditions of land-cover for the three periods: period 1 (LULC with weather data from 1970 to 1989); period 2 (NLCD 1992 with weather data from 1990 to 1999); and period 3 (NLCD 2001 with weather data from 2000 to 2009).

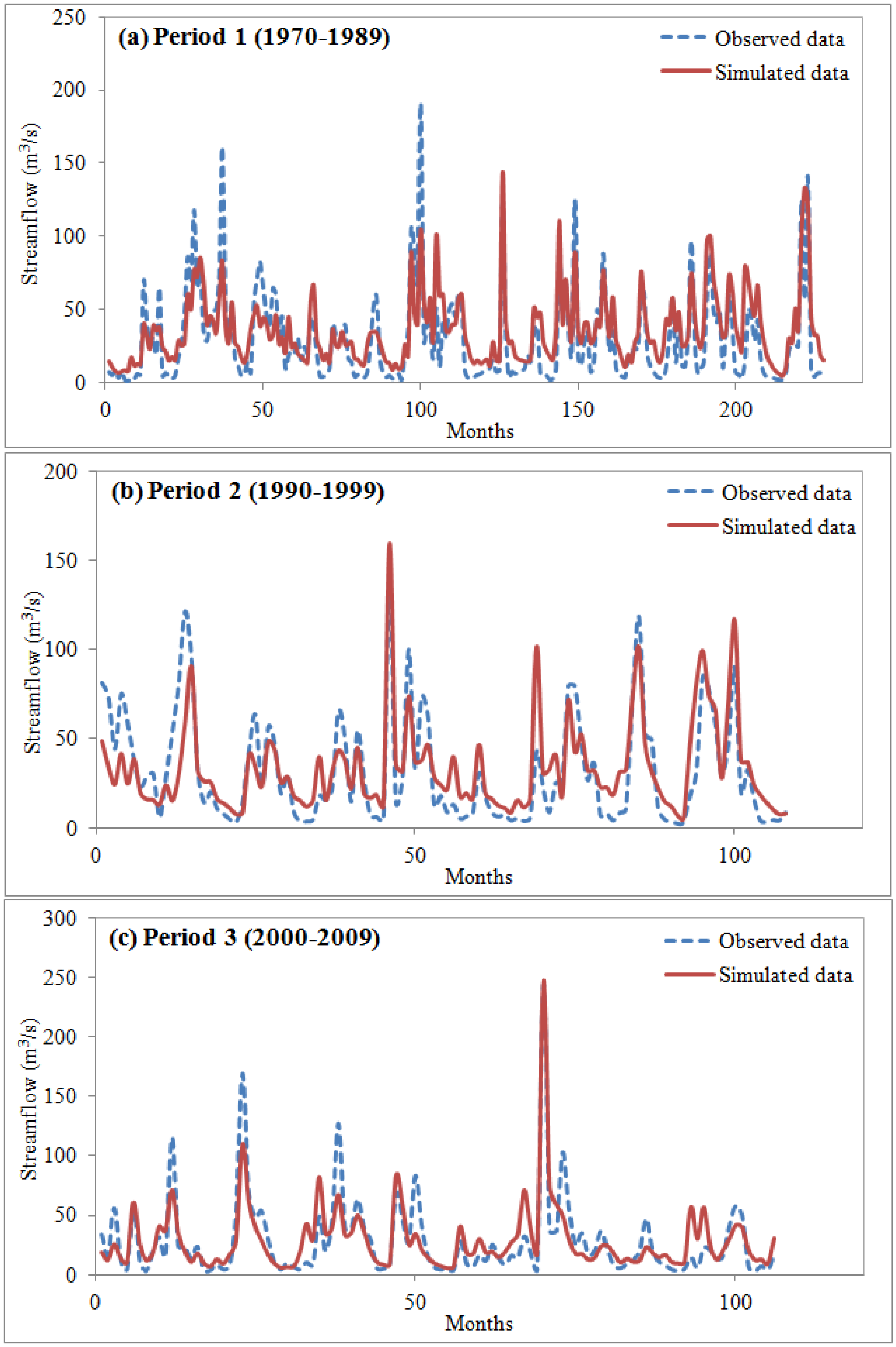

Figure 2.2. Monthly observed and simulated streamflows for the three periods; (a) Period 1 (1970-1989), (b) Period 2 (1990-1999), and (c) Period 3 (2000-2009).

2.4 Results

2.4.1 Changes in temperature and precipitation

Figure 2.3 and 2.4 show the historical changes of the annual average temperature and annual total precipitation from 1970 to 2009 based on four weather stations. The annual average temperature and annual total precipitation trends are subdivided into three different periods and analyzed in Figure 2.3 (b) and 2.4 (b) (period 1: 1970-1989, period 2: 1990-1999, and period 3: 2000-2009).

In general, annual average temperature and annual total precipitation show an increasing pattern although the magnitude of each trend is different. Annual average temperature shows a slight increasing trend with a slope of 0.021 for a forty year period from 1970 to 2009 (Figure 2.3 (a)). The annual average temperatures for the three study periods increased by 0.7 ˚C from period 1 to period 3, as annual average temperature for periods 1, 2, and 3 were 18.8 ˚C, 19.1 ˚C, and 19.5 ˚C, respectively (Table 2.4). Period 1 had a decreasing pattern in the annual average temperature, and periods 2 and 3 had an increasing pattern (Figure 2.3 (b)). Although the study area experienced a mixed pattern of decrease and increase in temperature, a slight increase in temperature occurs over the forty year period.

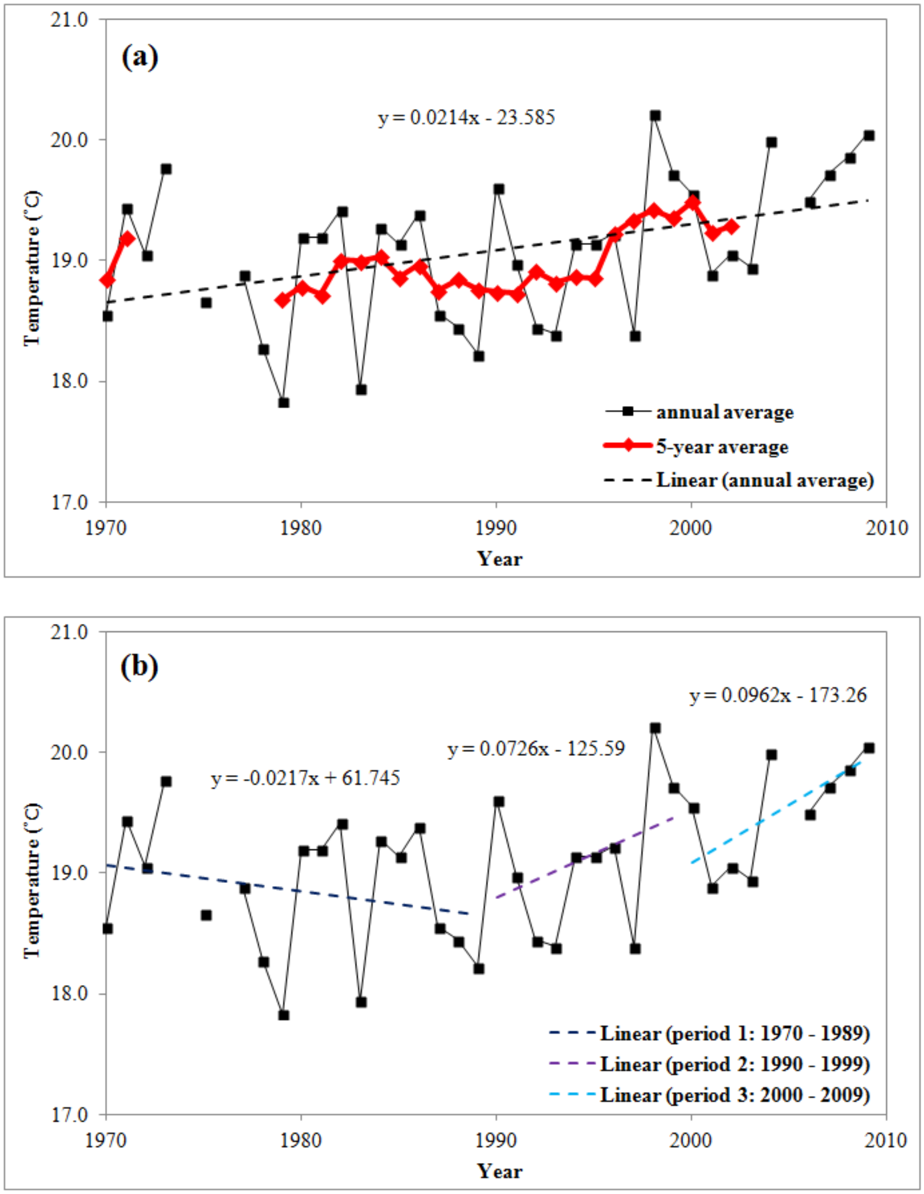

Figure 2.3. Historical temperature change in the study area during the period (1970-2009); (a) Historical changes of the annual average temperature and the five year average temperature from 1970 to 2009 and (b) Trend analysis for the temperature for the three periods (1970-1989, 1990-1999, and 2000-2009) used in the SWAT models.

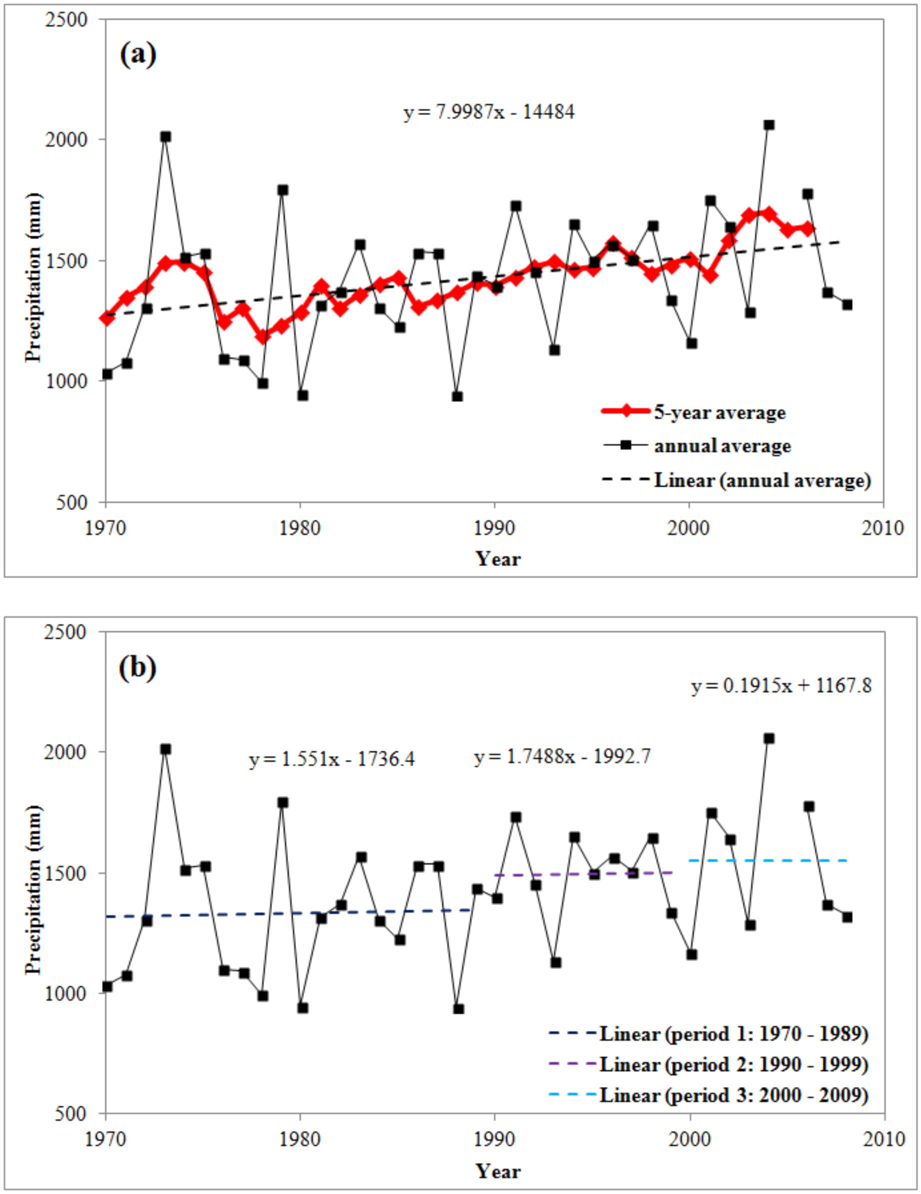

Figure 2.4. Historical precipitation change in the study area during the period (1970-2009); (a) Historical changes of the annual total precipitation and the five year average precipitation from 1970 to 2009 and (b) Trend analysis for the precipitation for the three periods (1970-1989, 1990-1999, and 2000-2009) used in the SWAT models.

Previous studies reported increasing patterns of temperature for a humid subtropical climates ranging 1 ~ 2 ˚C increase (Neff et al., 2000; Limaye et al., 2001; IPCC, 2007; Nobrega et al., 2011; Candela et al., 2012; Sun et al., 2012). For example, Mid-Atlantic basins with a humid subtropical climate had a 1.5 ˚C increase in temperature from 1945 to 1995 (Neff et al., 2000), and the humid subtropical climate in the Wales River basin in England recorded an increased temperature of 1.2 ˚C from 1957 to 1988 (Arnell, 1992). Moreover, Severn Valley basin in Australia, with a humid subtropical climate showed an increase 2 ˚C in temperature from 1950 to 1985 (Fitzgerald and Walsh, 1987), and the humid climate in the north of Spain had a 1.2 ˚C increased temperature over last twenty years (Candela et al., 2012). Compared to the previous studies, the study area indicates a lower increase rate in temperature during the forty years of observation.

In the study area, during the forty year of observation period, annual total precipitation had increased 16.3 % from 1,333.7 mm to 1,551.6 mm, for the period 1 to period 3 (Table 2.4), and the overall trend shows a relatively higher slope of 7.998 (Figure 2.4 (a)). All three observation periods have increasing patterns with the period 2 being the period of highest slope. Cases of previous studies reported a 15 % increase for Mid Atlantic basins (Neff et al., 2000), 15 % increase for the Wale River basin (Arnell, 1992), a 10 % increase for Seven Valley basin (Fitzgerald and Walsh, 1987), and a 15 % increase for the north of Spain (Candela et al., 2012). The magnitude of change in annual total precipitation shows an increase in precipitation for the forty year period whereas a lower increase in temperature occurred.

Table 2.4 shows the statistics of temperature and precipitation trends for the period of observation. The table includes mean, minimum, maximum, standard deviation, and coefficient of variation. The standard deviation is not a useful measure for comparison of data sets with different means because larger means tend to have larger standard deviation. The minimum temperature was 17.8 ˚C in period 1, whereas the maximum temperature was 20.2 ˚C in period 2. The coefficient of variation for temperature ranged from 0.02 to 0.03, and period 3 had the lowest coefficient of variation, 0.02. This suggested that period 3 had the smallest variance in temperature and showed a relatively even distribution.

Table 2.4. Annual mean temperature and annual total precipitation for the three observed periods (source: Southern Regional Climate Center, 2010).

	Temperature (˚C)					Precipitation (mm)				
	Mean	MIN	MAX	STD	CV	Mean	MIN	MAX	STD	CV
Period 1 (1970 - 1989)	18.8	17.8	19.8	0.6	0.03	1,333.7	944.4	2,022.0	292.0	0.22
Period 2 (1990 - 1999)	19.1	18.4	20.2	0.6	0.03	1,495.3	1,133.7	1,736.0	175.8	0.12
Period 3 (2000 - 2009)	19.5	18.9	20.1	0.5	0.02	1,551.6	1,166.2	2,067.9	309.5	0.20
Overall (1970 - 2009)	19.1	17.8	20.2	0.6	0.03	1,422.1	944.4	2,067.9	280.0	0.20

MIN: minimum, MAX: maximum, STD: standard deviation, CV: coefficient of variation

The minimum and maximum precipitation, however, was 944.4 mm in period 1 and 2,067.9 mm in period 3. The mean precipitation had an increasing trend from period 1 to period 3. Also, the lowest coefficient of variation was 0.12 in period 2. This implies that period 2 had the smallest variance and change in precipitation. According to IPCC (2007), global temperature and precipitation generally increased by 0.7 ˚C and 2%, respectively, from 1901 to 2000. USGCRP (2009) reported that annual temperature and precipitation have increased by 1.1˚C. A 5 % increase has been noted for North America from 1955 to 2005.

The above seem reasonable when considered in the context that global climate had shown different patterns in each of the periods regarding warming (1901-1940: greenhouse gas, 1966-2000: El Nino, greenhouse gas) and cooling (1941-1965) (IPCC, 2001; IPCC, 2007). The IPCC (2007) suggested that global temperature has increased rapidly since 1970s because of human influence. The IPCC also suggested that changes have been observed in the amount, frequency, and intensity of precipitation since the 1970s. Previous studies (Arnell, 1992; Neff et al., 2000; Limaye et al., 2001; Nobrega et al., 2011; Candela et al., 2012), however, did not focus on the factors, such as minimum, maximum, and standard deviation. Comparing this present study results with previous the results from studies, suggest that temperature and precipitation generally increased in period 2 and 3, but no significant correlation occurred between temperature and precipitation in each period.

2.4.2 Changes in land cover

Figure 2.5 shows the historical land-cover maps of the study area. These maps show land cover in 1970s/1980s, 1990s, and 2000s, respectively. To maintain a consistent land-cover classification, the land-cover maps are reclassified into seven classes: 1) grass, 2) bush/shrub, 3) forest, 4) developed land, 5) barren land, 6) water, and 7) crop land. The classification of grass includes herbaceous vegetation, such as grass and perennials. The bush/shrub category includes bush or shrub vegetation, which is less than six meters high. The forest category includes deciduous forest, evergreen forest, and mixed forest. The developed-land category includes residential, urban settlement, transportation, and industrial land. The barren-land category includes bare rock, sand, and clay. The water category includes rivers and lakes. The crop-land category includes cultivated crops and pasture land. These classes were created by manual interpretation of remote sensing data so that they all mentioned the SWAT 2009 input/output file documentation (http://swatmodel.tamu.edu/documentation/). The areas and percentage of the historical land-cover types during the three different time periods are given in Figure 2.6 and Table 2.5.

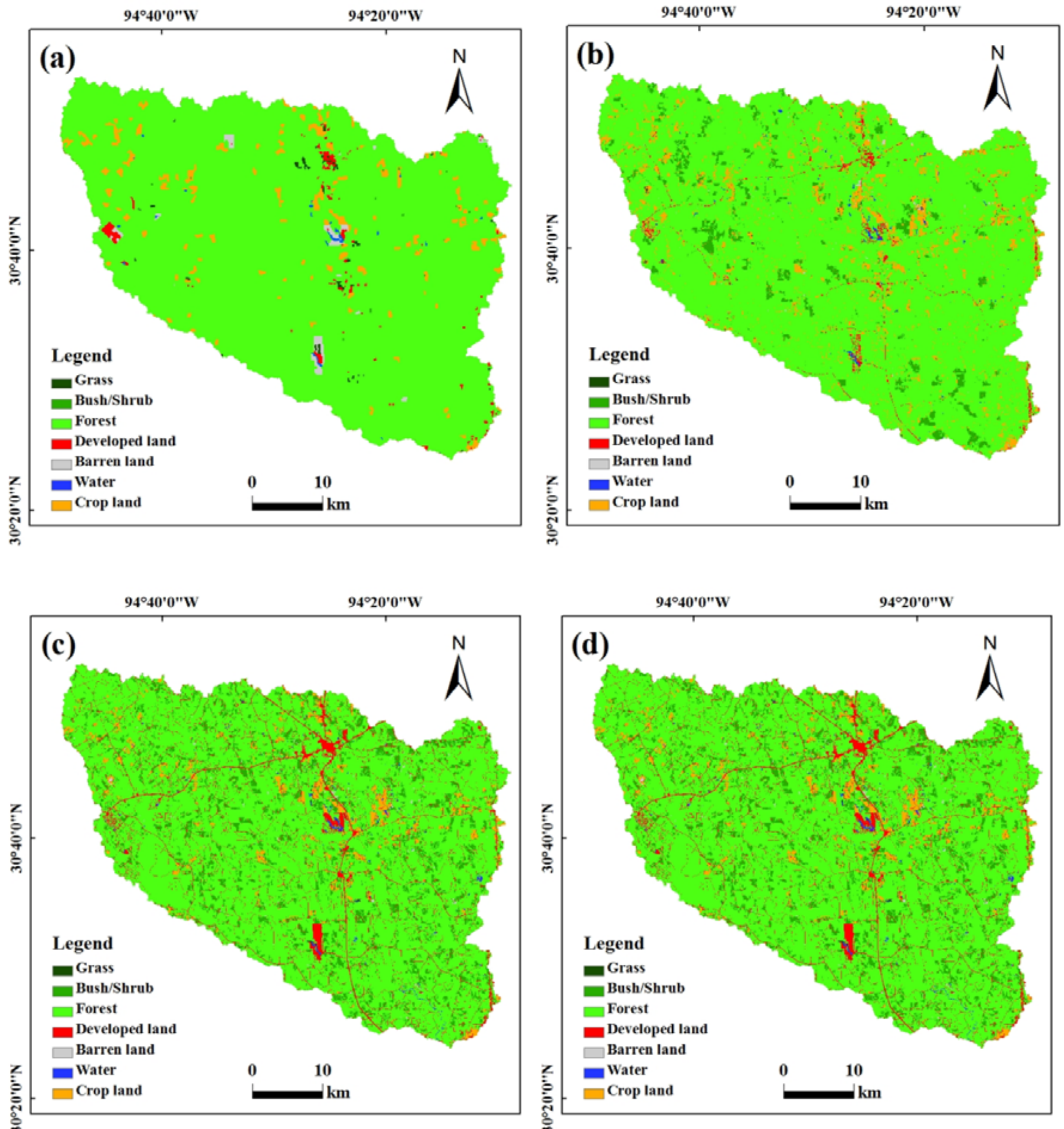

Figure 2.5. Land-cover maps of the study area; (a) LULC, (b) NLCD 1992, (c) NLCD 2001, and (d) NLCD 2006.

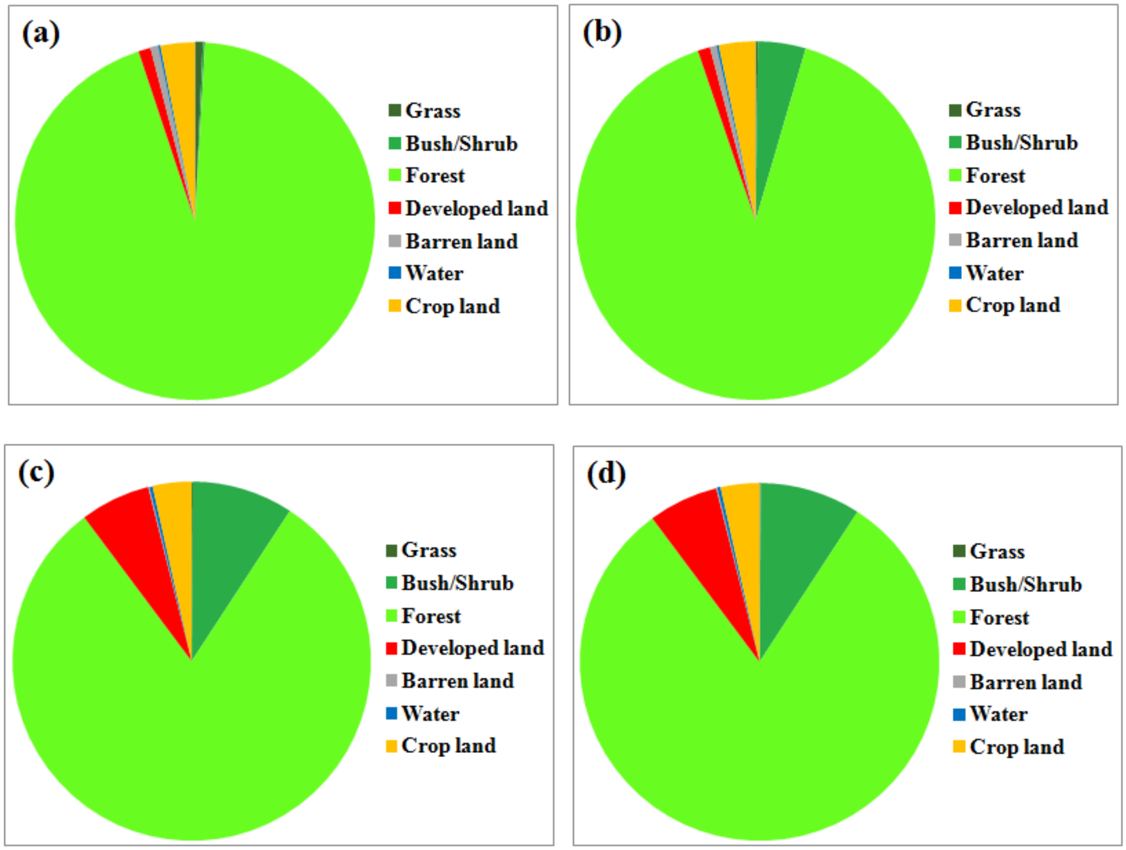

Figure 2.6. Changes of land-cover types in the study area based on land-cover maps; (a) LULC, (b) NLCD 1992, (c) NLCD 2001, and (d) NLCD 2006.

Table 2.5. The area (km^2) and area percentage (%) for each land-cover type in the study area are based on the land-cover data for specific time period.

	G	BS	F	D	B	W	C	Total
LULC	14.8 km^2 (0.7%)	4.6 km^2 (0.2%)	2,087.7 km^2 (94.0%)	23.8 km^2 (1.1%)	14.4 km^2 (0.7%)	4.7 km^2 (0.2%)	71.0 km^2 (3.1%)	2,221.0 km^2 (100.0%)
NLCD1992	4.4 km^2 (0.2%)	95.5 km^2 (4.3%)	2,005.6 km^2 (90.3%)	24.2 km^2 (1.1%)	14.0 km^2 (0.6%)	5.1 km^2 (0.2%)	72.2 km^2 (3.3%)	2,221.0 km^2 (100.0%)
NLCD2001	2.7 km^2 (0.1%)	202.1 km^2 (9.1%)	1,790.1 km^2 (80.6%)	138.8 km^2 (6.3%)	2.7 km^2 (0.1%)	5.8 km^2 (0.3%)	78.8 km^2 (3.5%)	2,221.0 km^2 (100.0%)
NLCD2006	2.2 km^2 (0.1%)	202.1 km^2 (9.1%)	1,790.1 km^2 (80.6%)	138.8 km^2 (6.3%)	2.7 km^2 (0.1%)	5.8 km^2 (0.3%)	79.3 km^2 (3.5%)	2,221.0 km^2 (100.0%)
Changes	-12.4 km^2 (-0.6%)	197.5 km^2 (8.9%)	-297.6 km^2 (-13.4%)	115.0 km^2 (5.2%)	-11.7 km^2 (-0.6%)	1.1 km^2 (0.1%)	8.3 km^2 (0.4%)	

G: grass, BS: bush/shrub, F: forest, D: developed land, B: barren land, W: water, C: crop land

Table 2.6. Summary of the comparison of land-cover change between the three different time periods; (a) LULC - NLCD 1992 and (b) NLCD 1992 - NLCD 2001.

(a)		NLCD 1992							LULC
		G	BS	F	D	B	W	C	Total
LULC	G	4.4 km^2 (29.7%)	8.8 km^2 (59.5%)	-	-	-	0.4 km^2 (2.7%)	1.2 km^2 (8.1%)	14.8 km^2 (100.0%)
	BS	-	4.6 km^2 (100.0%)	-	-	-	-	-	4.6 km^2 (100.0%)
	F	-	82.1 km^2 (3.9%)	2,005.6 km^2 (96.1%)	-	-	-	-	2,087.7 km^2 (100.0%)
	D	-	-	-	23.8 km^2 (100.0%)	-	-	-	23.8 km^2 (100.0%)
	B	-	-	-	0.4 km^2 (2.8%)	14.0 km^2 (97.2%)	-	-	14.4 km^2 (100.0%)
	W	-	-	-	-	-	4.7 km^2 (100.0%)	-	4.7 km^2 (100.0%)
	C	-	-	-	-	-	-	71.0 km^2 (100.0%)	71.0 km^2 (100.0%)
NLCD 1992 Total		4.4 km^2 (100.0%)	95.5 km^2 (100.0%)	2,005.6 km^2 (100.0%)	24.2 km^2 (100.0%)	14.0 km^2 (100.0%)	5.1 km^2 (100.0%)	72.2 km^2 (100.0%)	2,221.0 km^2

Table 2.6. Continued.

(b)		NLCD 2001							NLCD 1992
		G	BS	F	D	B	W	C	Total
NLCD 1992	G	2.7 km^2 (61.4%)	-	-	-	-	0.6 km^2 (13.6%)	1.1 km^2 (25.0%)	4.4 km^2 (100.0%)
	BS	-	95.5 km^2 (100.0%)	-	-	-	-	-	95.5 km^2 (100.0%)
	F	-	106.6 km^2 (5.3%)	1,790.1 km^2 (89.3%)	103.4 km^2 (5.2%)	-	-	5.5 km^2 (0.2%)	2,005.6 km^2 (100.0%)
	D	-	-	-	24.2 km^2 (100.0%)	-	-	-	24.2 km^2 (100.0%)
	B	-	-	-	11.2 km^2 (80.0%)	2.7 km^2 (19.3%)	0.1 km^2 (0.7%)	-	14.0 km^2 (100.0%)
	W	-	-	-	-	-	5.1 km^2 (100.0%)	-	5.1 km^2 (100.0%)
	C	-	-	-	-	-	-	72.2 km^2 (100.0%)	72.2 km^2 (100.0%)
NLCD 2001 Total		2.7 km^2 (100.0%)	202.1 km^2 (100.0%)	1,790.1 km^2 (100.0%)	138.8 km^2 (100.0%)	2.7 km^2 (100.0%)	5.8 km^2 (100.0%)	78.8 km^2 (100.0%)	2,221.0 km^2

G: grass, BS: bush/shrub, F: forest, D: developed land, B: barren land, W: water, C: crop land

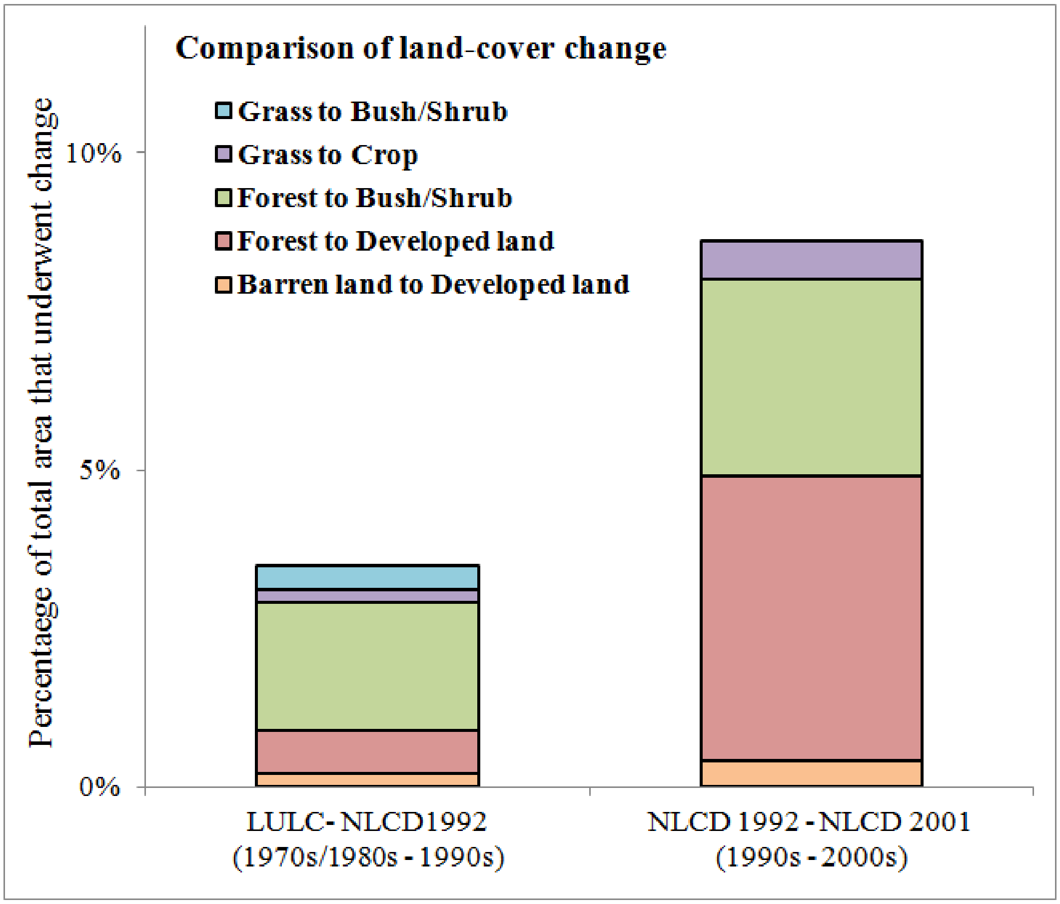

Figure 2.7. Major components of the comparison of land-cover change for the study area in LULC - NLCD 1992 and NLCD 1992 - NLCD 2001.

The comparison of land-cover change is also applied to detect the change pattern in each type of land-cover quantitatively. The comparison of land-cover change is an effective method to identify the change history in each type of land-cover between two land-cover data (i.e., between LULC and NLCD 1992, the decreased area of barren land was converted into developed land or grass?). The comparison of land-cover change gives the knowledge of the conversion in types of land-cover for the study area (Mattikalli, 1994; Long et al., 2007). The comparison of land-cover change was calculated the area of land-cover converted from each land-cover into each of the remaining land-cover, using ArcGIS spatial analyst module (Mattikalli, 1994). Table 2.6 and Figure 2.7 show the comparison of land-cover change in each type of land-cover data for the three different time periods; (a) LULC (1970s/1980s) - NLCD 1992 and (b) NLCD 1992 - NLCD 2001.

Changes in land cover from 1970s/1980s to 1990s

Vegetative land cover for 1970s/1980s makes up ~95 % of the area and barren land is <0.7 %. Because almost 96 % of the area is either natural vegetation or barren land, one can see that human intervention was minimal during the time period (Table 2.5). In 1990s, vegetation, barren land, and crop land accounted for 94.8%, 0.6%, and 3.3%, respectively (Table 2.5). Compared to 1970s/1980s, no major changes occurred in percentages of developed land and water. Crop land was evenly distributed in the study area, but barren land was located mostly in the central part of the study area (Figure 2.5 (a)). As shown in Table 2.6 (a), 8.1 % of grass land cover was converted to crop land, as grass cover decreased from 14.8 km^2 to 4.4 km^2 during the twenty-year period. Moreover, 3.9 % of forest cover was converted to bush/shrub; bush/shrub cover increased from 4.6 km^2 to 95.9 km^2 (Figure 2.7 (a)).

Between the two time periods, 2.8 % of the barren land cover was converted to developed land as the resulted of human activities. The predominant trend in land-cover change from 1970s/1980s (LULC) to the 1990s (NLCD 1992) can be summarized as conversion of forest to bush/shrub, with a minimal change occurring in grass and barren land to crop land and developed land.

Changes in land cover from 1990s to 2000s

Considerable changes in land cover occurred from the 1990s to the 2000s. Grass and forest cover decreased from 0.2 % and 90.3 % to 0.1 % and 80.6 %, respectively, whereas bush/shrub cover increased from 4.3 % to 9.1 % (Table 2.5). Total vegetation cover (i.e., the sum of grass, bush/shrub and forest) decreased from 94.8 % to 89.8 %. In addition, a significant decrease of barren land cover was occurred from 14.0 km^2 to 2.7 km^2 during the same time period. However, developed land and crop land increased from 1.1 % to 6.3 % and from 3.3 % to 3.5% in 2000s, respectively (Table 2.5). As shown in Table 2.6 (b), 25.0 % of the grass cover was converted to crop land, which indicates main human intervention occurred in the area. Approximately 5.3 % of the forest cover was converted to bush/shrub. And, during the same time period a significant portion (80%) of barren land was converted to developed land (Table 2.6 (b) and Figure 2.7 (b)).

In general, the trend in land-cover change can be summarized as conversion of forest to bush/shrub and, grass and barren land to developed land and crop land. Comparing early 2000s land cover to late 2000s, no changes appear to have occurred in the developed land cover, barren land cover, and water areas during the five years interval 2001 to 2006 whereas small changes in grass cover to crop land cover were occurred.

During the forty years of observation, the study area has increased in developed land cover and cropland cover as total vegetation cover (sum of grass, bush/shrub, and forest) decreased. Also, the general trend of decreased grass cover and forest cover and an increase in bush/shrub cover occurred. The study area has experienced an obvious warming trend and increased precipitation, however, the result in land-cover changes during the same time period combined with some level of human impact create a complicated picture of change. This can lead one to suggest that both climate warming and anthropogenic influence are responsible for the change, but one cannot determine which, warming or human played the dominant role.

2.4.3 Change in water resources

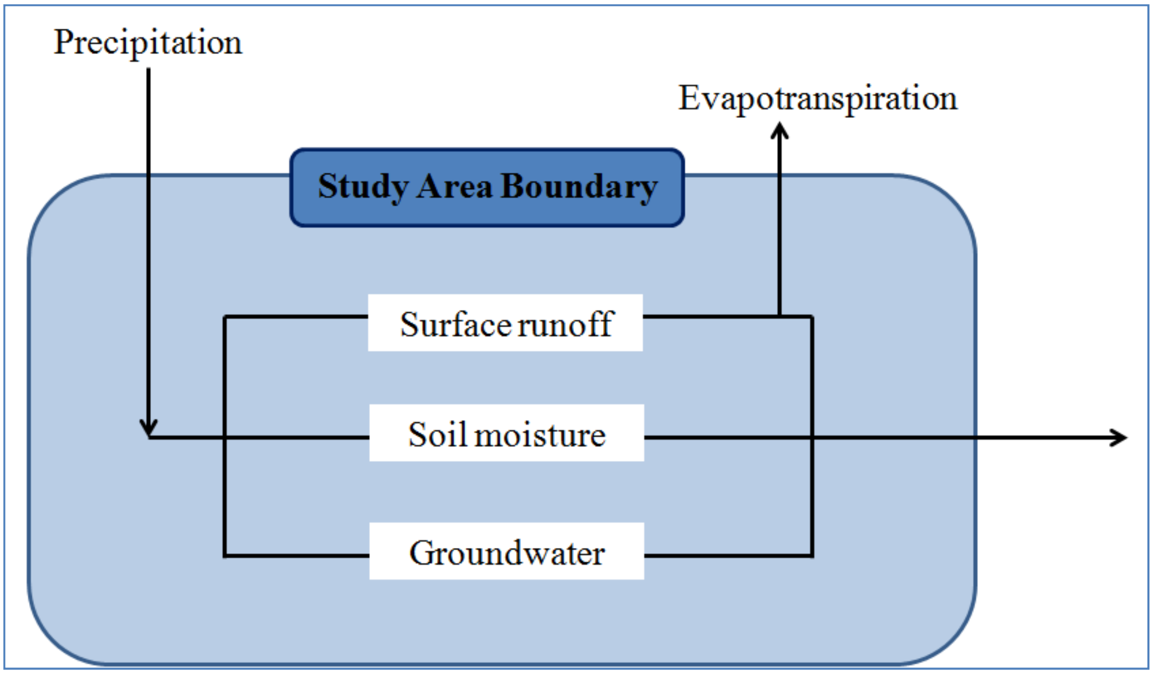

Figure 2.8. Schematic representation of water resources in the study.

The SWAT model was used to simulate annual changes in the water resources for a forty-year period (1970-2009). The components used in the simulation were precipitation, surface runoff, groundwater discharge, soil water content, and evapotranspiration (Figure 2.8). The results are displayed in Figure 2.9 and Table 2.7. The annual total volume and the proportion of precipitation in each component, including the proportion of each component to the total annual precipitation, are summarized in Table 2.8. It is important to note that because SWAT does not provide a means to simulate water storage, the water storage was estimated. The water storage was calculated by using the mass balance equation of the hydrologic cycle: water storage as:

$$W_S = P_I - \sum (R_S + W_G + W_{SC} + E) \qquad (1)$$

where W_S is water storage, P_I is precipitation, R_S is surface runoff, W_G is groundwater discharge, W_{SC} is soil water content, and E is evapotranspiration. Figure 2.10 shows the overall proportion of each component from 1970 to 2009.

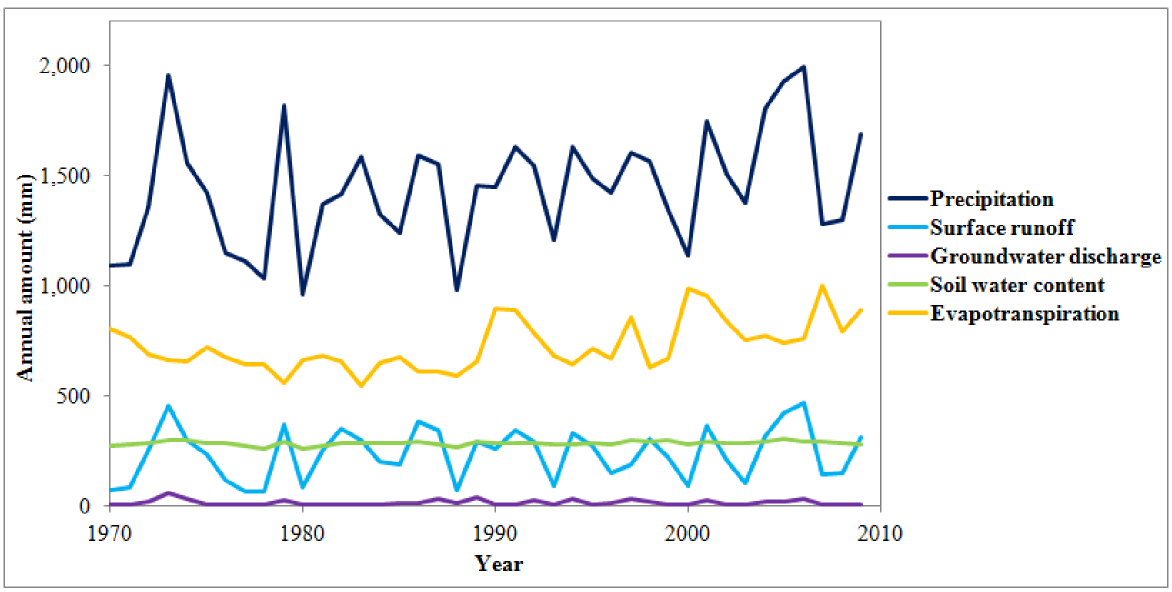

Figure 2.9. Annual total amount of precipitation, surface runoff, groundwater discharge, soil water content, and evapotranspiration simulated by SWAT for the period from 1970 to 2009. The simulated precipitation is based on the observed precipitation data. Missing data are automatically simulated by SWAT.

Table 2.7. Historical annual amount of each hydrological component as derived by SWAT.

	Surface runoff mm	Groundwater discharge mm	Soil water content mm	Evapotranspiration mm
Period 1 (1970-1989)	221.5	14.1	279.0	690.3
Period 2 (1990-1999)	243.1	13.2	283.8	770.4
Period 3 (2000-2009)	254.8	12.8	286.5	829.1
Changes	15.0 %	-9.2 %	2.7 %	20.1 %

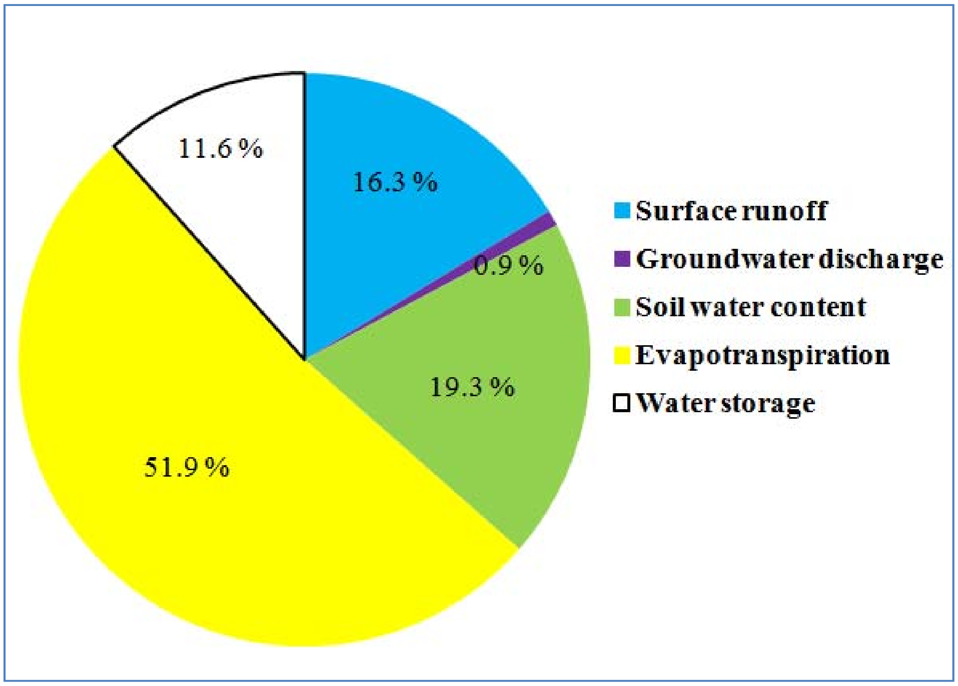

Figure 2.10. Proportion of each component of the total precipitation from 1970 to 2009. The water storage is calculated from the mass balance equation of the hydrologic cycle.

Table 2.8. Historical annual volume and the proportion of precipitation in each hydrological component as simulated by SWAT (Mton= mega ton).

	Surface runoff		Groundwater discharge		Soil water content		Evapotranspiration	
	Mton	%	Mton	%	Mton	%	Mton	%
Period 1 (1970-1989)	492	16.4	31	1.0	620	20.6	1,534	51.1
Period 2 (1990-1999)	540	16.4	29	0.9	631	19.1	1,712	51.8
Period 3 (2000-2009)	566	16.2	28	0.8	637	18.2	1,842	52.7
Overall (1970-2009)	533	16.3	30	0.9	629	19.3	1,696	51.9

Surface runoff

Annual total surface runoff for periods 1, 2, and 3 were 212.5 mm, 243.1 mm, and 254.8 mm (Table 2.7). These account for 16.4 %, 16.4 %, and 16.2 % of total annual precipitation for the respective periods (Table 2.8). As the values show, the percentage contribution to total annual precipitation is somewhat stable for the forty years of the study period, however, surface runoff did increase by 15.0 % during the three periods along with a 16.3 % increase in precipitation. From 1970 to 2009, the annual average volume of surface runoff is 533 mega ton suggesting that ~16.3 % of the precipitation becomes direct surface runoff in the study area (Table 2.8). It is interesting to note that although there is a change in temperature and an increasing trend in precipitation, surface runoff remains relatively stable over the time period (Table 2.8 and Figure 2.8).

Groundwater discharge

Changes in groundwater discharge during the forty years of study show a decreasing pattern whereas total annual precipitation shows an increasing pattern. Total annual groundwater discharge was 14.1 mm in period 1, 13.2 mm in period 2, and 12.8 mm in period 3 (Table 2.7). The contribution to total water was 1.0 %, 0.9 %, and 0.8 % (Table 2.8). An interesting and important fact that groundwater discharge decreased by 9.2 % and showed a generally decreasing pattern from 1970 to 2009 is important for the future (Table 2.7). The annual average volume of groundwater discharge is 30 mega ton with ~0.9 % of precipitation going into groundwater discharge during the three periods (Table 2.8). Groundwater discharge decreased in proportion and also decreased in actual amount from 31 mega ton to 28 mega ton (Table 2.8). This pattern runs counter to the general conception of a positive relationship between precipitation and groundwater discharge. This fact is especially important as the study area experienced increasing precipitation during the time period. This fact of the reverse pattern suggests that the decline is not caused by a change in the climate but rather caused by increased human use of water for irrigation and municipal use.

Soil water content

For the period 1970 - 2009, the annual average volume of soil water content was 629 mega ton and ~19.3 % of the precipitation become soil water (Table 2.8). The total annual soil water content ranged from 279.0 mm in period 1 to 286.5 mm in period 3, and increase of 2.7 % during the forty years of observation (Table 2.7). The proportion to the total annual precipitation, however, decreased from 20.6 % to 18.2 % from period 1 to period 3 (Table 2.8). Although overall soil water content increased, a relatively smaller portion of precipitation contributed to the soil water content. Given a 16.3 % increase in precipitation along with a change in temperature, the changes in soil water content appear to have been minimally affected by the relatively large increase in precipitation. Again, this finding is contrary to the general positive relationship between the precipitation and soil water content (Figure 2.8). Again this finding suggests that the cause is related to additional parameters other than climate change. For example, land-cover changes caused by human intervention might play a major role.

Evapotranspiration

Evapotranspiration shows an increasing pattern over the forty years of study. The values for the three time period are: 690.3 mm, 740.4 mm, and 847.1 mm (Table 2.7). A 16.3 % increase in precipitation occurred at the same time, evapotranspiration increased by 20.1 %, which would result in higher evaporation (Table 2.7). From 1970 to 2009, the annual average volume of evapotranspiration was 1,696 mega ton (Table 2.8). Although change in temperature during the forty years was relatively stable, change in precipitation increased. Evapotranspiration showed a similar increase compared to precipitation (Figure 2.8). Whereas it is well known that temperature is a major factor controlling evapotranspiration, the impact on evepotranspiration in the study area is mainly linked to increased precipitation. In other words, more water to be evaporated.

2.5 Discussion

This study investigated the impact of changes in temperature and precipitation on water resources for a basin in a humid subtropical climate. The study area is located in the Neches watershed of east Texas. This particular area was chosen as a possible area to indentify the impact of changes in climate on water resources more accurately, because it was thought to have minimum human intervention. In addition, forty-years of weather records, including temperature and precipitation, was available and the landcover change was available for three periods representing 1970s/1980s, 1990s, and 2000s, respectively. The weather record and landcover data served as input to a SWAT model that simulated changes in water resources over the forty-year period.

2.5.1 Changes in temperature and precipitation

The changes in temperature and precipitation in the study area from 1970 to 2009 can be summarized as a 0.7 ˚C increase in temperature and a 16.3 % increase in precipitation from 1,333 mm to 1,551 mm (Table 2.4). The parameters affecting temperature variation are considered to be land cover (Neff et al., 2000), green house gasses, and air pollution. Previous studies on humid climate systems reported temperature increases as being affected by land-cover change resulting from human development, CO_2 increase, and air pollution (Wolter et al., 1999; Neff et al., 2000; Wang et al., 2008; Li et al., 2009). Developed lands have relatively high heat capacity and high albedos resulting in increases in temperature (Arnell, 1992). Land-cover change affects local variations in temperature. On the other hand, increases in global temperatures are enhanced by CO_2 increase and air pollution associated with human activities (Wolter et al., 1999; USGCRP, 2009). It is interesting to note that a simulation showed an increase in global temperature without human impact (USGCRP, 2009). The study area was selected with the expectation of minimal human activities in order to observe changes in temperature and precipitation assumed to be the result of changes in the natural climate system. Because developed land only comprise ~6 % of the watershed during the last period of the study, the temperature variation in the study area is considered to be somewhat the result of natural change in the system (Table 2.5). The temperature variation of this watershed with minimal human impact shows a lower increase, compared to other climate studies (Neff et al., 2000; Limaye et al., 2001; IPCC, 2007; Nobrega et al., 2011; Candela et al., 2012; Sun et al., 2012) on humid climate. Thus, temperature change in the study area is not significant.

Previous studies (Eagleson, 1978; Fitzgerald and Walsh, 1987; Ziegler et al., 2005; Clasessens et al., 2006; IPCC, 2007) describe changes in land cover being one of the parameters affecting precipitation. In general, developed lands decreased soil water and reduced trees evaporation rates but increased albedo and reradiated radiation, which eventually results in a decrease in precipitation (Fitzgerald and Walsh, 1987; Ziegler et al., 2005; Clasessens et al., 2006). In addition, it is well known that vegetation can produce an increase in precipitation, because vegetation roots store soil water contents and vegetation leaves control transpiration rates, which are connected to increases in precipitation (Eagleson, 1978). On a global scale, air pollution and aerosols resulting from human activities affect the solar radiation pathway and it can result in changes in air circulation resulting changes in precipitation patterns (IPCC, 2007).

The study area had a 16.3 % increase in precipitation from 1970 to 2009. This is a little higher rate increase compared to previous studies (Fitzgerald and Walsh, 1987; Arnell, 1992; Neff et al., 2000; Candela et al., 2012). Land cover patterns affecting local precipitation in the study area is dominated by natural vegetation with minimal amount of developed land. During forty years of observation, changes in land cover can be summarized by decrease of forest from 94.0 % to ~81 %, increase in bush/shrub from 0.2 % to ~9 %, and increase of developed land from ~1 % to ~6 % (Table 2.5). Based on the general relationship between land cover and precipitation, the study area has not experienced a major increase in precipitation. Thus, we suggest that the land-cover changes in the study are is not significant enough to affect local precipitation. Thus, we do consider that the precipitation increase in the study area might have some effect associated with the natural climate system or global climate controller, which could be air circulation patterns.

2.5.2 Changes in land cover

As an interconnected system, changes in land cover can have an effect on local temperature and precipitation (Giambelluca, 2005; USGCRP, 2009; Pang et al., 2012). Variations in temperature and precipitation are primarily controlled by regional air circulation and geographic characteristics of the natural climate system (USGCRP, 2009). The impact of human interference on land cover in the study area can be summarized by the conversion of bush/shrub (0.2 % to 9.1%) and increases in developed land (1.1 % to 6.3 %) and crop land (3.1 % to 3.5 %).

In a natural system, climate affects the types of vegetation and distribution. Temperature affects density and distribution, and precipitation influences types of vegetation. For example, grass is a dominant vegetation type where annual mean precipitation is no more than 500 mm, whereas forest is a major vegetation type where annual mean precipitation is greater than 1000 mm (Woodward, 1987; Lenihan et al., 2003; Chuai et al., 2012). Bush/shrub is more widely distributed than other vegetation types because it is relatively less sensitive to changes in precipitation and temperature (Lenihan et al., 2008; Brummer et al., 2012). Also, frequent extreme weather (i.e., storms and drought) may decrease the amount of vegetation in humid climates (Bachelet et al., 2001; Kelly and Goulden, 2008; Sun et al., 2012). On the other hand, distribution of vegetation is also influenced by human impact. Changes in vegetation distribution can be affected by various human activities, including population growth, immigration of people, and settlement policies (Bachelet et al., 2001). Moreover, land-cover change by human activities is more significant and rapid in a relatively short period of time whereas the natural adjustment of land cover to climate variation responds slowly (Li and Yeh, 2004; Viger et al., 2011). As briefly mentioned in the previous paragraphs (Chapter 2.3.2), Table 2.5 and 2.6 showed that ~9 % of the study area was converted from forest and grass to bush/shrub, and ~6 % of the study area was converted to developed and crop lands from forest, grass, and barren land during forty years of observation. Thus, the conversion of grass to bush/shrub suggests it could be linked to changes in the natural climate system, whereas the conversion to developed and crop is the result of human activities. Although the study area was selected to represent an area with minimal human intervention, the land-cover changes resulting from human activities account for nearly 6 % of land-cover changes in the study area. It took only tens of years to change as human activities occur in the study area from 1990s to 2000s (Table 2.5). As the study area experienced increase in precipitation and relatively stable temperature, distinct increase in bush/shrub was observed. This natural conversion is different from previous studies (Woodward, 1987; Lenihan et al., 2003; Chuai et al., 2012), where forest increases when precipitation increases with certain levels of temperature. This relationship infers that a link between vegetation and extreme hydrologic events and human activities exists. This current study could not clearly identify the reason because historical data are lacking on extreme events, such as flood, drought, and heavy rainfall.

2.5.3 Changes in water resources

A hydrologic system consists of various components including precipitation, surface runoff, groundwater discharge, soil water, evapotranspiration and water storage. Depending on the characteristics of a climate system, distribution of precipitation varies (IPCC, 2007; Schonwiese, 2008). The hydrologic system of the study area, which is classified as a humid subtropical climate, shows ~52 % of the precipitation is lost as evapotranpiration or stored as soil water content ~19 %, as surface runoff ~16 %, and as groundwater storage 0.9 %, respectively (Table 2.8). Water storage is estimated as ~12 % of precipitation based on the mass balance equation (Figure 2.9). Previous studies (Lerner et al., 1990; Sun, 2004) suggested that an high portion of precipitation goes to groundwater recharge in a humid region. Sun (2004) observed that evapotranspiration / precipitation is ~48 %, surface runoff / precipitation is ~27 % and groundwater recharge / precipitation is ~25 % in New Jersey, a humid tropical climate, from 1917 to 2001. Sloto et al. (1991) reported that evapotranspiration / precipitation is ~47 % and surface runoff / precipitation is ~25 % in Jordan Creek region, Pennsylvania, a humid continental climate, from 1967 to 1986. Compared to previous humid climate studies (Sloto et al., 1991; Sun, 2004), the study area showed relatively higher evapotranspiration / precipitation and lower surface runoff / precipitation (Figure 2.9).

Surface runoff

Surface runoff is the portion of precipitation that is not evaporated, stored as soil water content, or filtered down to groundwater but flows into stream channels (USGCRP, 2009). Surface runoff generally has a similar pattern to that of precipitation (IPCC, 2007; Lespinas et al., 2010). On the other hand, if land cover is influenced by human impacts, especially developed land, surface runoff is affected. Surface runoff will be greater than the increase in precipitation because developed land (i.e., impervious surface) decreases the rate of infiltration and increase the rate of flow and the volume of surface runoff (Sun, 2004; Giambelluca, 2005; Claessns et al., 2006). During the forty years of observation, the study area had an increase in developed land. Although developed land had a ~5 % increase during last forty years, surface runoff increased 15.0 % whereas precipitation increased 16.3 % (Table 2.7). As variation in precipitation and surface runoff show a very similar pattern (Figure 2.8), it is assumed that surface runoff is linked to change in climate, which is causing an increase in precipitation.

Groundwater discharge

As defined in the SWAT input/output file documentation (2009), groundwater discharge is defined as the groundwater contribution to streamflow. It is well known that areas of high precipitation experience increases in groundwater discharge, whereas areas with low precipitation undergo decreases in groundwater discharge (IPCC 2007; Ma et al., 2009). Many studies report that groundwater discharge is more directly affected by human intervention than climate change because groundwater slowly responded to climate change (Gleick, 1987; Rosenberg et al., 1999; IPCC, 2007; Ferguson and Maxwell, 2010). For example, Rosenberg et al. (1999) reported that groundwater discharge began a constant decreased from 1950s in the upper Ogallala aquifer by human activities whereas precipitation increased by 10 %. This study found that groundwater discharge decreased by ~9 % and showed a decreasing pattern from 1970 to 2009 whereas precipitation increased ~16 % (Table 2.7). According to the results from the SWAT model, groundwater discharge would account for only 0.9 % of precipitation where as a small change in ground water use can affect changes in groundwater discharge (Table 2.8). The land-cover change in the study area shows an increase in crop land and developed land, and the population of Tyler County steadily increased from 12,417 in 1970 to 21,766 in 2010 (US Census Bureau, 2010).

Although crop land and developed land account for a relatively small portion of land in the study area (Table 2.5), the main source of agricultural and municipal water in the study area is ground water (USGS Groundwater resources of Tyler county, 1968). Groundwater levels for southeast Texas has gradually decreased since the 1950s (USGS Groundwater Resource, 2009A). This change can be inferred that groundwater discharge in the study area is more influenced by human activities including irrigation and municipal use rather than climate change. Also, because of the relatively small size of the aquifer, human activities may have a significant effect on groundwater discharge.

Soil water content

Soil water content is the available water capacity a soil can be hold or store (USGCRP, 2009; SWAT 2009 input/output file documentation). Soil water content is influenced by temperature and precipitation (Giambelluca, 2005; IPCC, 2007; Zhou et al., 2011). High temperature can result in an increase in the rate of evaportranspiration, which eventually decreases the soil water content whereas high precipitation can directly increases soil water content (Giambelluca, 2005; IPCC, 2007). Moreover, some studies report that soil water content can be also affected by land cover (Fontaine et al, 2001; McMahon et al., 2003; USGCRP, 2009; Kim and Wang, 2007; Joh et al., 2011). Previous studies show that a decrease in vegetation and an increase in developed land can have a negative impact on soil water content (Fontaine et al., 2001; Giambelluca, 2005; Kim and Wang, 2007; Hamdi et al., 2011). This current study discovered a 2.7 % increase in soil water content from 1970 to 2009 as precipitation increased by ~16 % (Table 2.7). During the forty-year period, total vegetation (sum of grass, bush/shrub and forest) decreased to 89.8 % and developed land increased to 6.3 % of the total area (Table 2.5). The ~16 % increase in precipitation was offset by a decrease in vegetation area, which resulted in a minimal increase in soil water content. It infers that soil water content is relatively sensitive to change in land cover.

Evapotranspiration

Evapotranspiration represents the total loss of water from the surface of Earth. Evapotranpiration can be increased by increased solar radiation and wind speed but reduced by high humidity (Mortsch et al., 2000; Dahm et al., 2002; Brummer et al., 2012). Limitations exist, however, with the monitoring records of evapotranspiration factors, such as solar radiation, wind speed, and humidity in historical observations because of measurement errors and technical issues associated with lack of sufficiation of instrumentation. Given the limited historical data for temperature and precipitation, this study includes a level of uncertainty in estimating evapotranpiration.

In humid environments, the rate of evapotranspiration generally has a similar trend to temperature because a humid climate is characterized by relatively high precipitation and high humidity. On the other hand, evapotranspiration can be influenced by land cover. Evapotranspiration decreases as vegetation decreases and developed land increases (Ma et al., 2009). High vegetation cover leads to increases evapotranspiration, whereas large areas of developed land decreases evapotranspiration (Eagleson, 1978; Clasessens et al., 2006; Peel et al, 2010). The current study area experienced ~20 % increase in evapotranspiration, which can be explained by a ~52 % of precipitation (Table 2.7 and 2.8). A USGCRP (2009) study suggested that the evapotranspiration/precipitation ratio is ~100% in arid environment, whereas the evapotranspiration/precipitation ratio is ~40% in humid environments. Compared to the USGCRP (2009) study, the estimates for the current study show higher evapotranspiration/precipitations than other humid environments. This fact may result from total vegetation (sum of grass, bush/shrub, and forest) decreasing very little from 94.9 % to 89.8 %. In other studies of humid climates (Clasessens et al., 2006; Ma et al., 2009; Peel et al, 2010) considerable area of developed land were presented.

Thus, it is important to note that small changes in land cover do not have a major contribution on evapotranpiration. Evapotranpiration generally follows the trend of precipitation (Figure 2.8) even if temperature is relatively stable. Thus, it is necessary to consider other factors in evapotranspiration including wind speed, solar radiation, and humidity to understand the relationship of evapotranspiration to climate change more clearly.

2.6 Conclusions

This study has evaluated the impact of changes in temperature and precipitation on water resources for a watershed in a humid subtropical climate for the period 1970 to 2009. The study area was originally selected as a watershed where human impact was minimal to examine the natural response of water resources changes in temperature and precipitation. For this study historical land cover data represents three different periods; 1970s/1980s, 1990s, and 2000s. SWAT simulations were run to investigate characteristics and variations in water resources for the three periods by incorporating land-cover changes for each period.

During the forty year of record, there was an increase in temperature by 0.7 ˚C; the increase was not a continuous positive change, rather a mixed pattern of decrease and increase. Although the period of observation is different than previous studies in areas with humid climates, the magnitude and proportion of temperature variation is a little lower than other studies. On the other hand, precipitation showed an increasing pattern of ~17 % increase during the study period. The rate of increase for precipitation is a little higher than studies of similar climate types. It is interesting to note that during the forty years temperature remained relatively stable, precipitation increased, conversion of bush/shrub increased 0.2 % to 9.1 %, developed land increased 1.1 % to 6.3 % and crop land increased 3.1 % to 3.5 %. All the increases were at the experience of forest which decreased from 94.0 % to 80.6 %, grass which decreased from 0.7 % to 0.1 %, and barren land which decreased from 0.7 % to 0.1 %.

The main trend in land-cover change was conversion of forest and grass to developed land and crop land; both of which are the result of anthropogenic intervention. Based on the spatial analysis of the land cover conversions, forest and grass to bush/shrub can be considered the result of natural process. The finding from the study suggest that human intervention directly affected land-cover change. However, changes in temperature and precipitation might have an impact. The period of observation was too small and the results were so insignificant that we cannot demonstrate that climate change has had an effect on land-cover change.

Climate is a complex system consisting of numerous entities. And, although this study was not able to demonstrate a direct link between climate change and water resources, this study did show change in a humid subtropical climate watershed over a forty year period of observation. The SWAT simulation did identify a 51.9 % evapotranspiration rate, 16.3 % surface runoff, 0.9 % groundwater discharge, and 19.3 % soil water content. It is important to note that 11.6 % of the precipitation becomes water storage. Compared to other studies of humid climates, this study shows a similar rate of evapotranspiration, within a 4 % difference, but surface runoff is significantly lower by a

10% difference. This suggests that developed land in previous studies might have contributed to higher surface runoff.

The important finding of this research showed a ~17 % in precipitation increases and a change in 5.6 % of land cover from grass, forest, and barren land to developed land and crop land. The SWAT simulation estimated a 15.0 % increase in surface runoff, a 9.2 % decrease in groundwater discharge, a 2.7 % increase in soil water content, and a ~20 % increase in evapotranspiration. Thus, small changes in land cover do not play significant role in the change of surface runoff because precipitation is a major controller of surface runoff whereas groundwater discharge can be affected by human impact and agricultural water use resulting in a negative trend. Soil water content has a more sensitively response to land-cover changes than to climate where precipitation increase was offset by the impact of land-cover change. Higher evapotranspiration is considered to be caused by vegetation dominated land cover.

3. A SEMI-ARID WATERSHED

3.1 Introduction

Water, an essential resource on Earth, is widely used for agriculture, human consumption, recreation, industry, and power generation. Water also serves an important role in public health and economic development. Water accounts for 70 % of the surface on Earth, but 97 % of the water contains salt. Only a very small fraction of the total water is available as a domestic water resource (USGCRP, 2009; Barron et al., 2012). As a result of expanding population and changing weather patterns, water resources are becoming increasingly scarce. An additional factor, which is impacting water as a sources is land cover changes (IPCC, 2007; Bao and Fang, 2009; Polebitski et al., 2011). Many parts of the world are facing serious problems with their water resources. The above mentioned use are resulting in stress on water system and water scarcity.

Water serves an especially important role in arid and semi-arid climates. Water is the most important factor regulating ecosystem processes in these climates, as a result of these environment are frequently water stressed (Ragab and Prudhomme, 2002; IPCC, 2007; USGCRP, 2009; Jarsjo et al., 2012).

Water resources can be affected by climate change (IPCC, 2007; Wiley et al, 2010; Cuo et al., 2011). Researchers have demonstrated that climate change intensifies the variations of precipitation and temperature, which directly influences changes in streamflow, runoff, and evapotranspiration (Davies and Simonovic, 2005; Li et al., 2009; Ma et al., 2009; Liping et al., 2012). Climate change can also enhance the frequency of floods and droughts in the future under differing climatic condition (IPCC, 2007; Li et al., 2009; Liu and Xia, 2011). In addition to climate change, land cover/land change resulting from human activities is considered as another factor that directly influences water resources. Anthropogenic activity involves the removal of vegetation, increase in developed land and a resulting increase in impervious area. The increase in impervious surface area can lead to an increase in runoff volume and a decrease in rates of infiltration rate (Giambelluca, 2005; Ma et al., 2009; Dixon and Earls, 2012). Land cover/land change can alter the hydrological cycle of a region by altering rate of runoff and infiltration. The changing rates subsequently can have a negative impact on soil moisture content (He et al., 2009; Dixon and Earls, 2012).

Arid and semi-arid climates occupy ~32 % of the land areas on Earth, which, incidentally, is the largest climate zone (Fraedrich et al., 2001; Kim et al., 2008). This climate type is mostly associated with the mid latitude western wind belts and restricted to western parts of North and South Americas, the northern part of Africa, the northwestern part of Asia, and the central part of Australia (Beck et al., 2000; Peel et al., 2007). Although generally considered to be sparsely population, there are cities with major populations located in the climate. For example, Tucson, Phoenix, Cairo, and Dubai. Beck et al. (2000) estimated that the area of arid climate has increased by 1.0 % from 1955 to 1995, and it will continue to increase in the future. Thus, it is necessary to understand the impact of various entities, including land use/land cover changes, climate change, can have on the water resources in arid or semi-arid climate regions.

Considerable studies have been undertaken to estimate the impact of various entities on water resources in an arid or semi-arid climate (Rosenberg et al., 1999; Seguis et al., 2004; IPCC, 2007; Jarsjo et al., 2012; Montenegro and Ragab, 2012). Rosenberg et al. (1999) studied the variation of the Ogallala aquifer region, US, as a result of changing climate and land-cover. The Ogallala aquifer region is dominated primarily by cropland with some developed land. Rosenberg et al. (1999) reported over a 15 % decreased in groundwater from 1951 to 1990 based on a HBM (Hydrological Balance Model), as precipitation decreased 10 % and temperature increased 2.5 °C along with increased human activities.

The Sahelian watershed in Africa, an arid climate, which is comprised of savanna land and developed land, experienced a 10 % decrease in precipitation and a 20 % decrease in surface runoff during the period from 1950 to 2000. SWAT models were employed comparing land-cover data sets from 1975 to 1992 (Seguis et al., 2004). Jarsjo et al. (2012) studied climate change and its impact on surface runoff for the Aral drainage basin, a semi-arid climate basin, in the Central Asia using data to compare 1961 to 1990. They found a 10 % decrease in surface runoff whereas temperature increased 2 °C and precipitation decreased 5 % based on the GCM (General Circulation Model) and developed land, agriculture, and forest land covers.

As briefly mentioned previously, waster resources can be influenced by either climate change or land-cover change or a combination of the two. To clearly understand the impact of climate change on water resources of a region, the impact of land-cover change resulting from human impact must be excluded from the research. Although previous research claimed to study climate change and its impact on water resources, most of the research is flawed, as it studied area that contained significant amounts of developed land cover, which clearly can mask how much of an impact is caused by climate change. It is difficult to exclude the impact of humans. Moreover, previous research used only one or two land-cover data sets in the simulations. Nevertheless, climate change can impact land-cover types and it also can impact water resources. This current research examines changes in temperature and precipitation, and the response of water resources to these changes for a semi-arid watershed, which has three different land-cover types. The period of study extends from 1970 to 2009.

The overall objective of this research is to assess the impact of changes in temperature and precipitation on water resources in a semi-arid watershed that has a minimal anthropogenic intervention during the period 1970 to 2009. The Soil and Water Assessment Tool (SWAT) model was used to model the impact of changes in temperature and precipitation on various hydrologic parameters that impact water resources. Three different land-cover data sets were used to simulate the realistic scenarios. This research provides significant information for the management of water resources in semi-arid climates and the response to these potential changes.

3.2 Study Area

The study area is located in northeast New Mexico, which is a part of the Upper Canadian River Basin (Figure 3.1). It has a total area of 5,289.9 km^2 and is located within Hydrologic Unit Code (HUC) 11080007. The study area extends across three counties of New Mexico; Harding, Union, and Colfax. Elevation in the study area ranges from 1,163 m to 2,551 m.

The geology, soils, and land use in the study area are all rather consistent. The geology of the study area consists of Miocene volcanic rocks and various Cretaceous deposits (USGS National Geologic Database, 2011). The major soil types in study area consist of Gruver (clay) and Springer (find sand) (USDA National Resources Conservation Service, http://soils.usda.gov/sdv/). The land use in the study area consists mainly of barren land, grass, bush/shrub, and forest. Undeveloped land accounts for ~98 % of the total area.

The study area is a predominantly semi-arid. The annual mean temperature is 11.3 °C, and the annual total precipitation is 398.3 mm; the mean annual temperature and average annual total precipitation is based on the data of from four climatic stations: Bueyeros, Mosquero, Pasamonte, and Roy (Western Regional Climate Center, 2010). The four climatic stations and one gaging station are all located in the study area and provide long term climatic and hydrologic data with a relatively dense observation network (Figure 3.1). Because of the minimal human intervention and data being available, this study area is assumed to provide optimal assessment for the investigation of changes in temperature and precipitation, and the response of water resources in a semi-arid to changes in the climate.

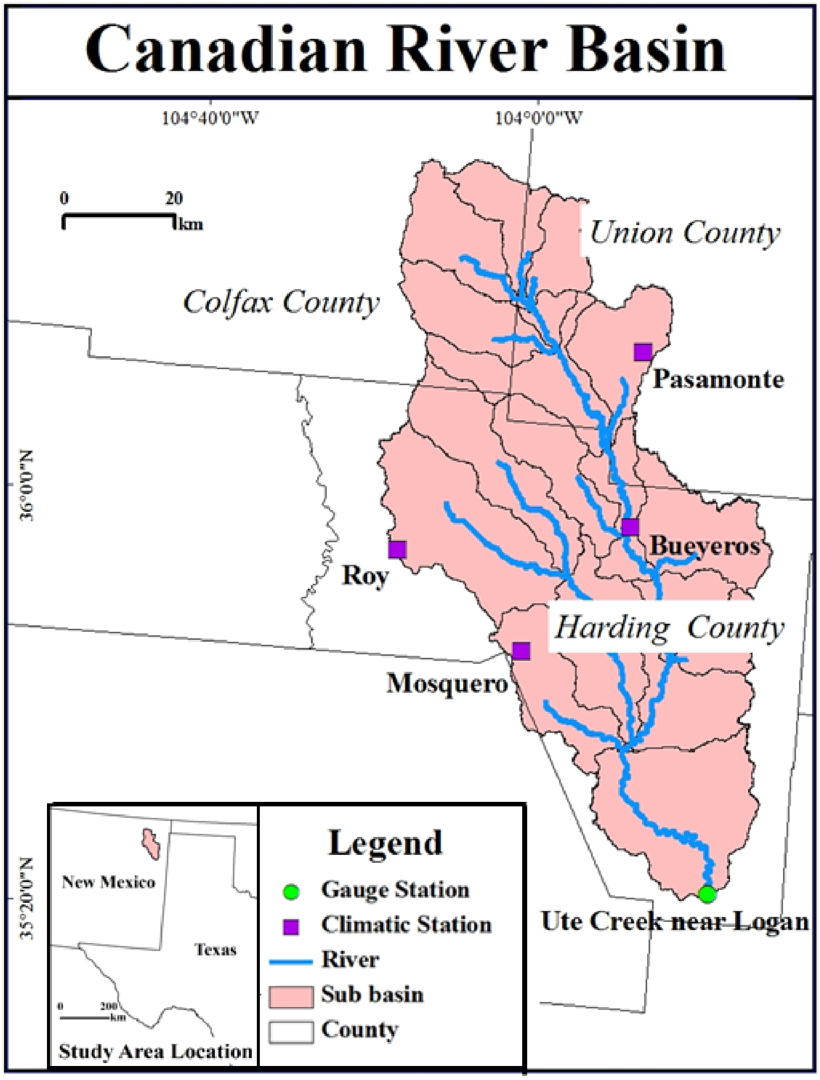

Figure 3.1. Location map of the study area with semi-arid climate.

3.3 Materials and Methods

3.3.1 Data

To assess the impact of changes in temperature and precipitation on the water resources of the study area, this research utilized daily-based weather data and hydrologic data collected on a daily basis, including temperature, precipitation, and streamflow from four weather stations and one hydrologic station for the period 1970 to 2009. The Soil and Water Assessment Tool (SWAT) model was applied to evaluate the impact of changes in temperature and precipitation on water resources in the study area. Input data for the SWAT model consisted of GIS based soil data (STATSGO), three land-cover data sets, and a Digital Elevation Model (Table 3.1).

Daily total precipitation and daily temperature data from 1970 to 2009 are from the National Climate Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA) and United States Department of Agriculture (USDA). The monthly and annual total precipitation were calculated from the daily data and used to do a trend analysis of changes in temperature and precipitation. The period 1950 to 1968 has considerable missing data because of irregular measurement or mechanical errors. For the missing periods of data, the SWAT model was used to simulate weather data to compensate for the gaps in the database. These data are considered sufficiently accurate for use in the study because the SWAT database provides weather information for 1,041 stations around the US (SWAT 2009 User's Guide documentation), allowing for the generation of data for the study area.

Stream-flow data were obtained from the National Water Information System (NWIS) of the US Geological Service (USGS) (http://waterdata.usgs.gov/nwis). One gauge station (07226500), provides continuous daily data from 1970 to 2009 and is located at the outlet of the upper Canadian River watershed. This gaging station was used to calibrate the SWAT model.

The State Soil Geographic (STATSGO) database provided soil data for the study area. The STATSGO is a digital soil map, which was created in 1994 by Natural Resources Conservation Service (NRCS). The STATSGO has a mapping scale of 1:250,000 and is can be used in hydrologic modeling of counties or small areas (Grassman et al., 2007; Geza and McCray, 2008). The STATSGO database provides the input calculating various SWAT soil parameters: soil hydrologic group, layer thickness, bulk density, available water capacity, and soil texture. The parameters can be extracted using the SWAT database.

A Digital Elevation Model (DEM) was obtained from the Earth Resource Observation and Sciences (EROS) of the United States Geological Survey (USGS) at a 30-m spatial resolution. The DEM was employed to build the stream network and to calculate degree of slope, channel length, and elevation in the SWAT model. An important point to understand is the SWAT model treats large watershed as a series of hydrological connected subbasins. Thus, the DEM was used to subdivided the watershed into subbasins. The elevation ranges from 1,163 m to 2,551 m with an average elevation of 1,635 m in the study area. The DEM was geo-referenced in the Universal Transverse Mercator (UTM) projection with the World Geodetic Systems - 1984 (WGS-1984) datum, located in the UTM Zone 13.

Land-cover data are critical component in a hydrological simulation using SWAT. Different time periods land cover data were used: (a) USGS Land Use and Land Cover (LULC), (b) USGS National Land Cover Database (NLCD) 1992, and (c) USGS NLCD 2001. The three land-cover data sets represented three different time periods in the SWAT model. The land-cover data were classified following the Anderson Land-Cover Classification System. The classes do not contain information on the density of vegetation (http://landcover.usgs.gov/classes.php).

Land Use and Land Cover (LULC) is historical data derived from USGS aerial photography from 1970s to 1980s. LULC consists of 9 land-cover categories and 37 sub-categories. The LULC data are mapped on the Universal Transverse Mercator (UTM) and referenced to the North American Datum of 1983 (NAD 83). The data for the continental US is mapped at a 1: 250,000 scale and a spatial resolution of 400 meters. LULC also provided hydrologic units, census counties, and land ownership on the land cover.

The National Land Cover Dataset (NLCD) 1992 was created in the early 1990s using Landsat Thematic Mapper (TM) data. NLCD 1992 consists of 9 land-cover categories and 21 sub-categories. The spatial resolution for the data is 30 meter. It is projected on an Albers Conic Equal Area projection. The data set includes information on topography, population, agricultural production, and soil characteristics.

The National Land Cover Dataset (NLCD) 2001 is based on the early 2000s Landsat Enhanced Thematic Mapper+ (ETM+) data. NLCD 2001 has 8 land-cover categories and 16 sub- categories. It is also projected on an Albers Conic Equal Area projection with 30-m resolution. The data set includes information on developed impervious surfaces and density of the tree canopy. NLCD 2001 provides standardized land cover components, which are useful for a variety of applications.

The NLCD 2006 is an updated version of NLCD 2001 using Landsat ETM+. The NLCD 2006 data set was generated from Landsat imagery between 2001 and 2006, and provides the same categories as the NLCD 2001.

The land-cover data from the three data sets have different sub-category legends used in the classification. To maintain consistency of land-cover classification, I reclassified the historical land-cover data into the following seven classes: 1) grass land, 2) bush/shrub land, 3) forest, 4) developed land, 5) barren land, 6) water, and 7) crop land. The grass category includes herbaceous vegetation and grass. The bush/shrub land category includes bush or shrub vegetation, including cactus. The forest category includes woody vegetation and evergreen forest, which are taller than six meters. The developed land category represents communication, transportation, infrastructure, and residential land. The barren land category includes bare rock. The water category includes rivers and lakes. The crop-land category includes agricultural land and crop land. These classes were mapped by manual interpretation of remote sensing data following SWAT 2009 input/output documentation (http://swatmodel.tamu.edu/documentation).

Table 3.1. The summary of the data used in this study.

Data type	Station name (site number)	Acquisition period	Source	Location
Precipitation	Bueyeros (291269)	1970-2009	NOAA, USDA	Lat: 36.0167, Lon: -103.7333
& Temperature	Mosquero (295937)	1970-2009	NOAA, USDA	Lat: 35.8000, Lon: -103.9333
	Pasamonte (296619)	1970-2009	NOAA, USDA	Lat: 36.3000, Lon: -103.7333
	Roy (297638)	1970-2009	NOAA, USDA	Lat: 35.9500, Lon: -104.2000
Stream discharge	Ute Creek near Logan (7226500)	1970-2009	NWIS (USGS)	Lat: 35.4385, Lon: -103.5257
Soil type	STATSGO	1994	NRCS	-
Digital elevation	30-m resolution DEM	2009	EROS (USGS)	-
Land cover type	LULC	1970s-1980s	USGS	-
	NLCD 1992	1992	USGS	-
	NLCD 2001	2001	USGS	-

3.3.2 SWAT model

The Soil and Water Assessment Tool (SWAT) is a hydrologic modeling tool designed to evaluate surface-water runoff, evapotranspiration, soil-water content, and groundwater discharge. SWAT has proven to be an effective tool for assessing water resources and land-use changes for a wide range of scales (Gassman et al., 2007). The ability of the model to simulate the hydrologic process has been confirmed by numerous studies at a range of spatial scales on monthly and annual time scales (Gassman et al., 2007; Zhang et al., 2009; Perazzoli et al., 2012).

SWAT has been chosen by the Environmental Protection Agency (EPA) to be one of the Better Assessment Science Integrating point and nonpoint Sources (BASINS) models (Gassman et al., 2007; Zhhang et al., 2010). It is also used extensively for modeling by the United States Department of Agriculture - Agricultural Research Service (USDA - ARS), the Natural Resource conservation Service (NRCS), and the Oceanic and Atmospheric Administration (NOAA) (Gassman et al., 2007).

Table 3.2. Sixteen parameters selected by sensitivity analysis for use with the study area.

No.	Parameter name	Description	Useful range
1	CN2	Runoff curve number	35 - 98
2	SOL_AWC	Soil available water capacity	0 -1
3	ESCO	Soil evaporation compensation factor	0 -1
4	ALPHA_BF	Baseflow alpha factor	0 -1
5	GWQMN	Threshold depth of water in shallow aquifer required for return flow to occur	0 - 5000
6	CH_K2	Effective hydraulic conductivity in man channel	0 - 150
7	REVAPMN	Threshold depth of water in shallow aquifer for re-evaporation to occur	0 -1
8	GW_REVAP	Groundwater re-evaporation coefficient	0.02 - 0.2
9	RCHRG_DP	Deep aquifer percolation fraction	0 -1
10	CH_N2	Manning's "n" value for the main channel	0.008 - 0.3
11	EPCO	Plant uptake compensation factor	0 -1
12	GW_DELAY	Groundwater delay time	0 - 500
13	SLSUBBSN	Average slope length	10 - 150
14	SURLAG	Surface runoff lag coefficient	0 - 10
15	CANMX	Maximum canopy storage	0 - 10
16	SMTMP	Snowfall temperature	0 -5

The SWAT model has numerous built-in tools to enhance evaluation of the data, the simulation process and the simulation outcomes. All of these are incorporated in the model software. One of the tools in the SWAT model is sensitivity analysis.

A sensitivity analysis is the process of evaluating the most sensitive parameters in the model simulation (Zhang et al., 2009). For example, the SWAT model has many parameters used to account for hydrological simulation. The sensitivity analysis determines the sensitive parameters that should be utilized in a specific SWAT calibration. Thus, this tool provides parameter guidance for the calibration step of the SWAT model. Based on the results of sensitivity analyses, sixteen highly-ranked parameters were selected for the current study. Table 3.2 shows the sixteen parameters selected through the sensitivity analysis. These parameters were used for calibration in the SWAT model.

A calibration is defined as the process of evaluation for the modeling results. The calibration involves comparing the simulated values against the observed values. Many statistics exist for hydrological model evaluation; Coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), Root-Mean-Square Error (RMSE), and Percent Bias (PBIAS). The R^2 and NSE are the most broadly used statistics to calculate the SWAT model (Jha et al., 2006; Moriasi et al., 2007; Cho and Olivera, 2009; Mango et al., 2011; Perazzoli et al., 2012).

The coefficient of determination (R^2) represents the degree of collinearity between observed and simulated data. R^2 describes the proportion of the total variance in the observed data that can be explained with the model. The result is equal to the square of Pearson's correlation coefficient (r). The formula for calculating the R^2 value is:

$$R^2 = \left\{ \frac{\sum_{t=1}^{n}(Q_{obs,i} - \bar{Q}_{obs})(Q_{sim,i} - \bar{Q}_{sim})}{\left[\sum_{t=1}^{n}(Q_{obs,i} - \bar{Q}_{obs})^2\right]^{0.5}\left[\sum_{t=1}^{n}(Q_{sim,i} - \bar{Q}_{sim})^2\right]^{0.5}} \right\}^2 \quad (1)$$

where, $Q_{obs,i}$ is the observed streamflows on the i^{th} day, $Q_{sim,i}$ is the simulated streamflows on the i^{th} day, and n is the number of observation. $\bar{Q}_{obs}$ is the average value of the observed streamflows and $\bar{Q}_{sim}$ is the average value of the simulated streamflows for the calibration period. R^2 ranges from 0.0 to 1.0, and higher values indicate better performances. The R^2 values which are higher than 0.5, are considered to be acceptable for an evaluation of a hydrological model (Moriasi et al., 2007). However, the R^2 is not sensitive to outlier or high extreme values and proportional data between simulated and observed values (Daly, 2006).

The Nash-Sutcliffe Efficient (NSE) describes how well the simulated and observed values fit to a straight line with a slope of 1. The NSE is a statistical method for predictive accuracy of hydrological models. The method determines the degree of the residual variance compared to the measured variance in a hydrological model. The NSE is defined as:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \bar{Q}_{obs})^2} \quad (2)$$

where, $\mathrm{Q}_{\mathrm{obs},i}$ is the observed streamflows on the i$^{\mathrm{th}}$ day, $\mathrm{Q}_{\mathrm{sim},i}$ is the simulated streamflows on the i$^{\mathrm{th}}$ day, and n is the number of observation. $\overline{\mathrm{Q}}_{\mathrm{obs}}$ is the average value of the observed streamflows for the calibration period. The NSE ranges between -∞ and 1. The closer the NSE values are to 1, the higher the accuracy of the model. NSE values greater than 0.75 are considered to be excellent, values above 0.65 are considered good, and values higher than 0.5 are regarded as satisfactory for hydrological model evaluations (Moriasi et al., 2007). The NSE is recommended for evaluating the accuracy of hydrological models by the American Society of Civil Engineers (Daly, 2006; Perazzoli et al., 2012).

Three different land-cover data sets, representing different time periods in the study area were used USGS Land Use and Land Cover (LULC), USGS National Land Cover Database (NLCD) 1992, and USGS NLCD 2001. As shown in Table 3.1, the land cover data sets were used to show land cover conditions for the three periods: period 1 (from 1970 to 1989), period 2 (from 1990 to 1999), and period 3 (from 2000 to 2009). Using these data sets, three SWAT models were developed for three simulation periods; period 1 (LULC with weather data from 1970 to 1989), period 2 (NLCD 1992 with weather data from 1990 to 1999), and period 3 (NLCD 2001 with weather data from 2000 to 2009). Land-cover data play an important role in enhancing output of the simulated hydrological model using SWAT. Thus, the impact of changes in temperature and precipitation on water resources can be better defined with a realistic hydrological model. In addition to the meteorological data land-cover data representing each temporal period for the study period are also used.

Table 3.3. Summary of three simulations and calibration values from the SWAT models.

Simulations	Years	Land-cover data	NSE	R^2
Period 1	1970-1989	LULC	0.69	0.70
Period 2	1990-1999	NLCD 1992	0.68	0.69
Period 3	2000-2009	NLCD 2001	0.77	0.79

Three SWAT models were calibrated on a monthly basis using the SWAT auto-calibration tool in SWAT. Table 3.3 shows the summary and calibration values in the three simulations from the SWAT model. The NSE and R^2 values range between 0.68 and 0.79 for the study area. Moriasi et al. (2007) suggested that NSE values >0.75 are considered excellent, values >0.65 are considered good, and values >0.5 are considered satisfactory for hydrological-model evaluation. Also, Moriasi et al. (2007) further concluded that R^2 values >0.5 are regarded as acceptable for model simulation. The performances of the calibrated models were generally satisfactory and acceptable simulations. Figure 3.2 shows the performance of the calibrated models for the three time periods. Each of the three simulations was calibrated independently, and the calibrated models were used to assess the relationship and impact of changes in temperature and precipitation on water resources in the study area.

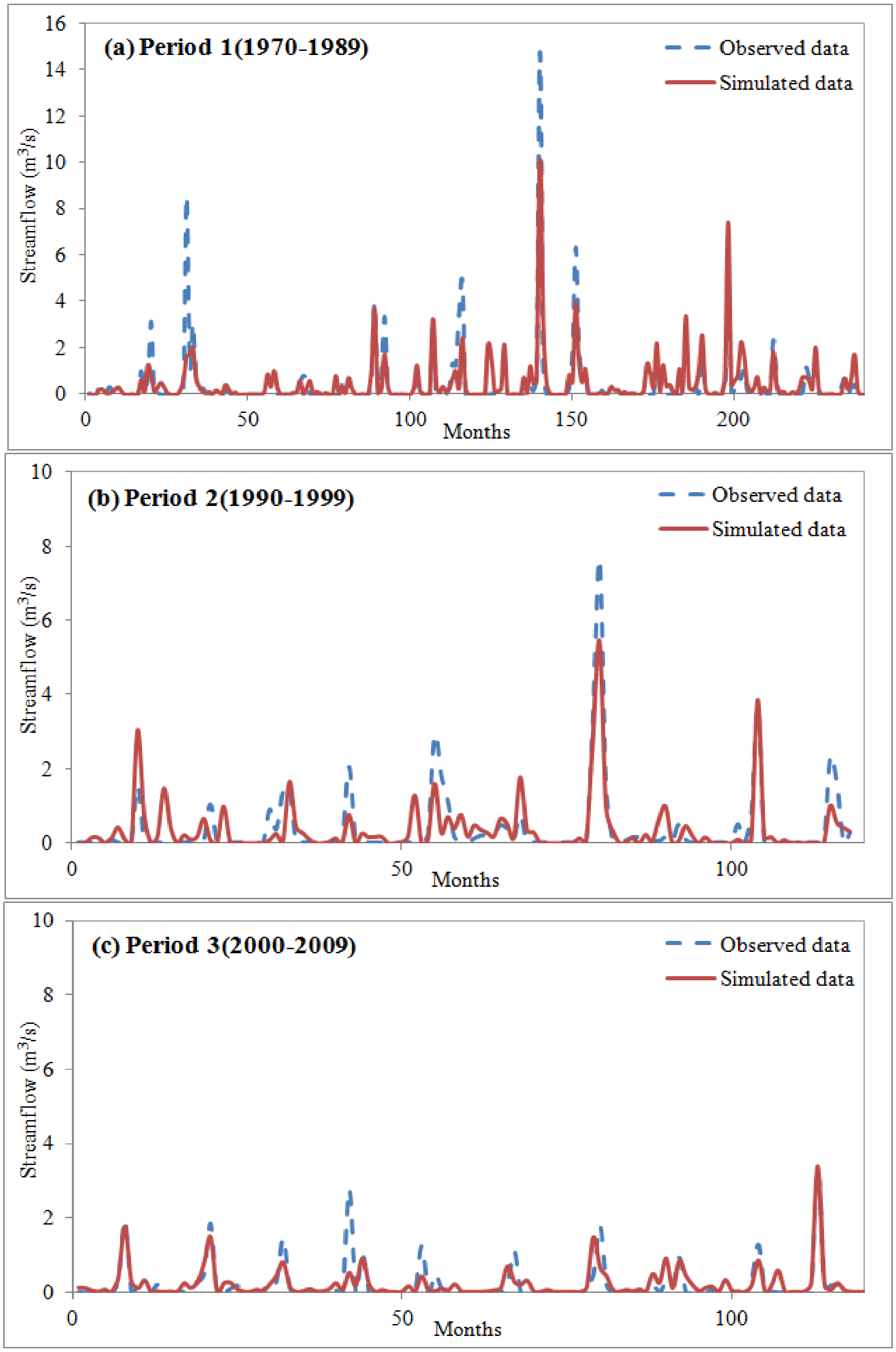

Figure 3.2. Monthly observed and simulated streamflows for the three periods; (a) Period 1 (1970-1989), (b) Period 2 (1990-1999), and (c) Period 3 (2000-2009).

3.4 Results

3.4.1 Changes in temperature and precipitation

The annual, average temperature and annual, precipitation total were compiled based on the historical weather data derived from four weather stations in the study area (Table 3.1). Figures 3.3 (a) and 3.4 (a) show the trend line, slope, and five-year average values for annual, average temperature and annual precipitation total from 1970 to 2009.

The annual, average temperature shows an increasing trend whereas annual precipitation total shows a decreasing trend for the study area (Figure 3.3 (a) and 3.4 (a)). During the forty years of observation from 1970 to 2009, annual, average temperature increased by 0.9 ˚C and had an increasing trend with a slope of 0.028 (Figure 3.3 (a)). Annual, average temperature for period 1, period 2, and period 3 were 11.0 ˚C, 11.3 ˚C, and 11.9 ˚C, respectively; a gradual increase can been seen (Table 3.4). On the other hand, Period 1 showed a decreasing pattern in annual, average temperature, whereas period 2 and 3 showed an increasing pattern. The temporal pattern for the study area shows a mixed trend of both decreasing and increasing temperatures (Figure 3.3 (b)). Previous research (Ragab and Prubhomme, 2002; Abdulla et al., 2009; Favreau et al., 2009; Jarsjo et al., 2012) found a temperature increase ranging from 1.5 ˚C to 2.5 ˚C in an arid or semi-arid climates over the observation of fifteen to fifty years.

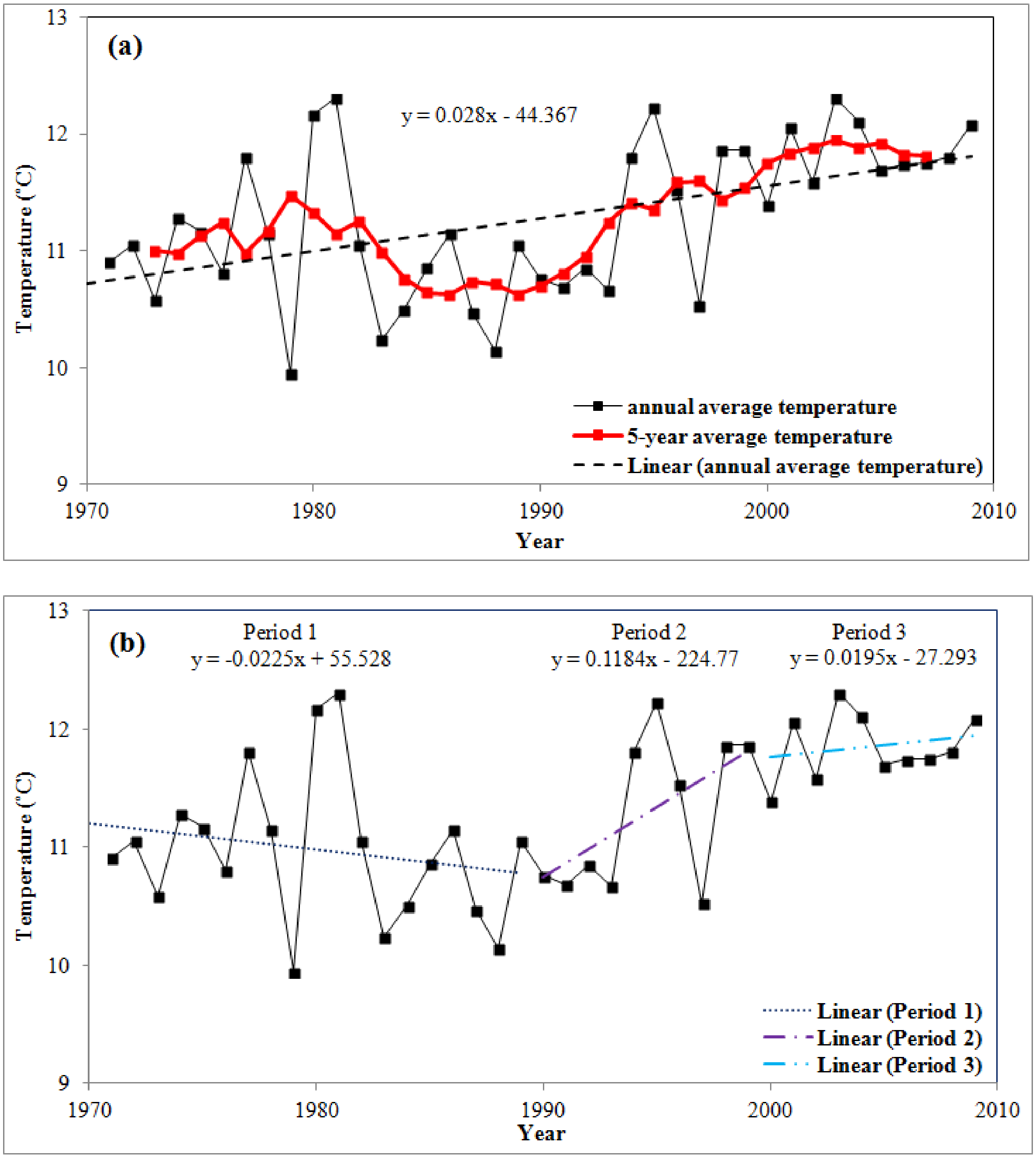

Figure 3.3. Historical change in temperature from 1970 to 2009 in the study area: (a) Historical changes in the annual average temperature during three periods (1970-2009) and (b) Trend analysis of the temperature by each period.

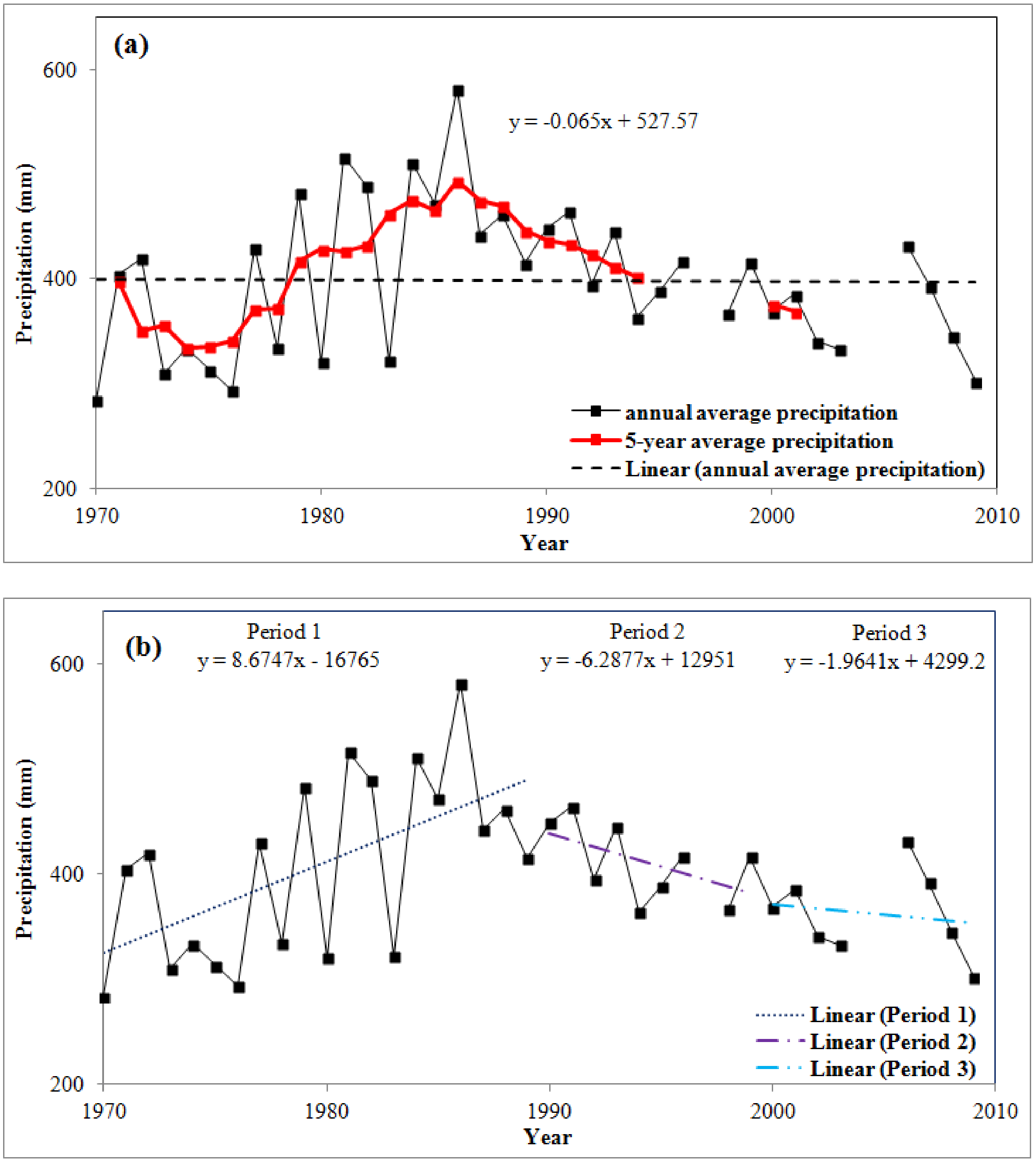

Figure 3.4. Historical change in precipitation from 1970 to 2009 in the study area: (a) Historical changes in the annual total precipitation during three periods (1970-2009) and (b) Trend analysis of the precipitation by each period.

Increasing temperatures has been documented for several semi-arid drainage basin around the world. For example, Favreau et al. (2009) showed that an arid watershed in southwest Niger had a 2.5˚C increase temperature from 1950 to 2007. Abdulla et al. (2009) noted a 1.5 ˚C increase in temperature for the Zarga River basin from 1980 to 1994. Also, Jarsjo et al. (2012) noted a 2 ˚C increase in temperature in Aral drainage basin over the last thirty years. Comparison of the temperature increase in the study area to the above mentioned study areas is lower ranging from 0.6 ˚C to 1.6 ˚C. Considering the relatively long observation of forty year for the current study, the temperature increase appears to show a moderate increase in temperature.

Annual total precipitation decreased by 10.9 % and had a decreasing trend with an overall slope of -0.065 for the study area during the forty-year period (Figure 3.4 (a)). The annual, precipitation total for period 1, period 2, and period 3 were 406.7 mm, 411.6 mm, and 362.2 mm, respectively (Table 3.4). The annual precipitation total for period 1 showed an increasing trend whereas period 2 and period 3 had a decreasing trend (Figure 3.4 (b)). Previous studies (Abdulla et al., 2009; Favreau et al., 2009; Jarsjo et al., 2012) reported 5 ~ 10 % decrease in precipitation for other arid or semi-arid climatic locations. For example, a 10 % decrease in precipitation was reported for southwest Niger during last fifty years (Favreau et al., 2009). The Zerga River basin experienced a 5 % decrease in precipitation from 1980 to 1994 (Abdulla et al., 2009). Moreover, the Aral Drainage basin had a 5 % decrease in precipitation over last thirty years (Jarsjo et al., 2012). Compared to these previous studies, the study area shows a relatively similar trend in precipitation with a 10.9 % decrease.

Estimated coefficients of variation were used to compare data sets with different means to achieve a normalized comparison (Table 3.4). The coefficient of variation for the annual temperature average is 0.06 for period 1 and 2 and 0.02 for period 3. Period 3 has the least variation and even distribution. The overall variation of annual temperature average is not significant. Coefficients of variations for annual total precipitation for the three periods are 0.22, 0.09, and 0.11. However, there appears a greater magnitude in variation in precipitation as compared to annual temperature average for the study area. It should be noted that the IPCC (2007) reported that global temperature and precipitation increased by 0.7 ˚C and 5 % during last one hundred years. USGCRP (2009) described that annual temperature and precipitation has increased by 1.1 ˚C and 5 % in US from 1955 to 2005. Based on the analysis of the weather data and comparison of data from the study area to data from previous studies, the changes in temperature and precipitation for the study area can be summarized as a low increase in temperature with a significant decrease in precipitation.

Table 3.4. Annual mean temperature and annual total precipitation for three time periods for the study area (source: Western Regional Climate Center, 2010).

	Temperature (˚C)					Precipitation (mm)				
	Mean	MIN	MAX	STD	CV	Mean	MIN	MAX	STD	CV
Period 1 (1970 - 1989)	11.0	9.9	12.3	0.6	0.06	406.7	283.5	582.0	88.0	0.22
Period 2 (1990 - 1999)	11.3	10.5	12.2	0.6	0.06	411.6	363.5	464.3	36.2	0.09
Period 3 (2000 - 2009)	11.9	11.4	12.3	0.3	0.02	362.2	302.0	431.5	42.7	0.11
Overall (1970-2009)	11.3	9.9	12.8	0.7	0.06	398.3	283.5	582.0	71.2	0.18

MIN: minimum, MAX: maximum, STD: standard deviation, CV: coefficient of variation

3.4.2 Changes in land cover

One can assume a causal relationship between changes in land cover and climate. Thus, as temperature and precipitation change, changes in land cover are assumed to occur changes in climate if no human intervention occurs. Land-cover changes were monitored over the observation period for the study area. The temporal periods were divided into three temporal periods based on three land-cover data representing each period. The these data sets for land-cover change are: LULC for 1970s/1980s (Figure 3.5 (a)), NLCD 1992 for 1990s (Figure 3.5 (b)), and NLCD 2001 and 2006 for the 2000s (Figure 3.5 (c) and (d)). The changes in land-cover types in the study area is summarized in Table 3.5 and Figure 3.6. In general, during the forty-year period, grass land, forest, developed land, and crop land have decreased from ~93 % to ~86 %, ~4 % to 1.4 %, 1.2 % to 0.1 %, respectively. A significant increase in bush/shrub land from 0.3 % to ~11 % occurred as precipitation decreased and temperature increased (Table 3.5). Table 3.6 and Figure 3.7 show the land-cover conversions in each land cover type for (a) LULC (1970s/1980s) - NLCD 1992, (b) NLCD 1992 - NLCD 2001, and (c) NLCD 2001 - NLCD 2006.

The land-cover conversion comparison was accomplished using ArcGIS® spatial analyst module (Mattikalli, 1994; Long et al., 2007). The decrease of developed land and crop land suggests diminishing human activities in the study area whereas decrease in grass land and increase in bush/shrub land is considered to be the result of a natural conversion.

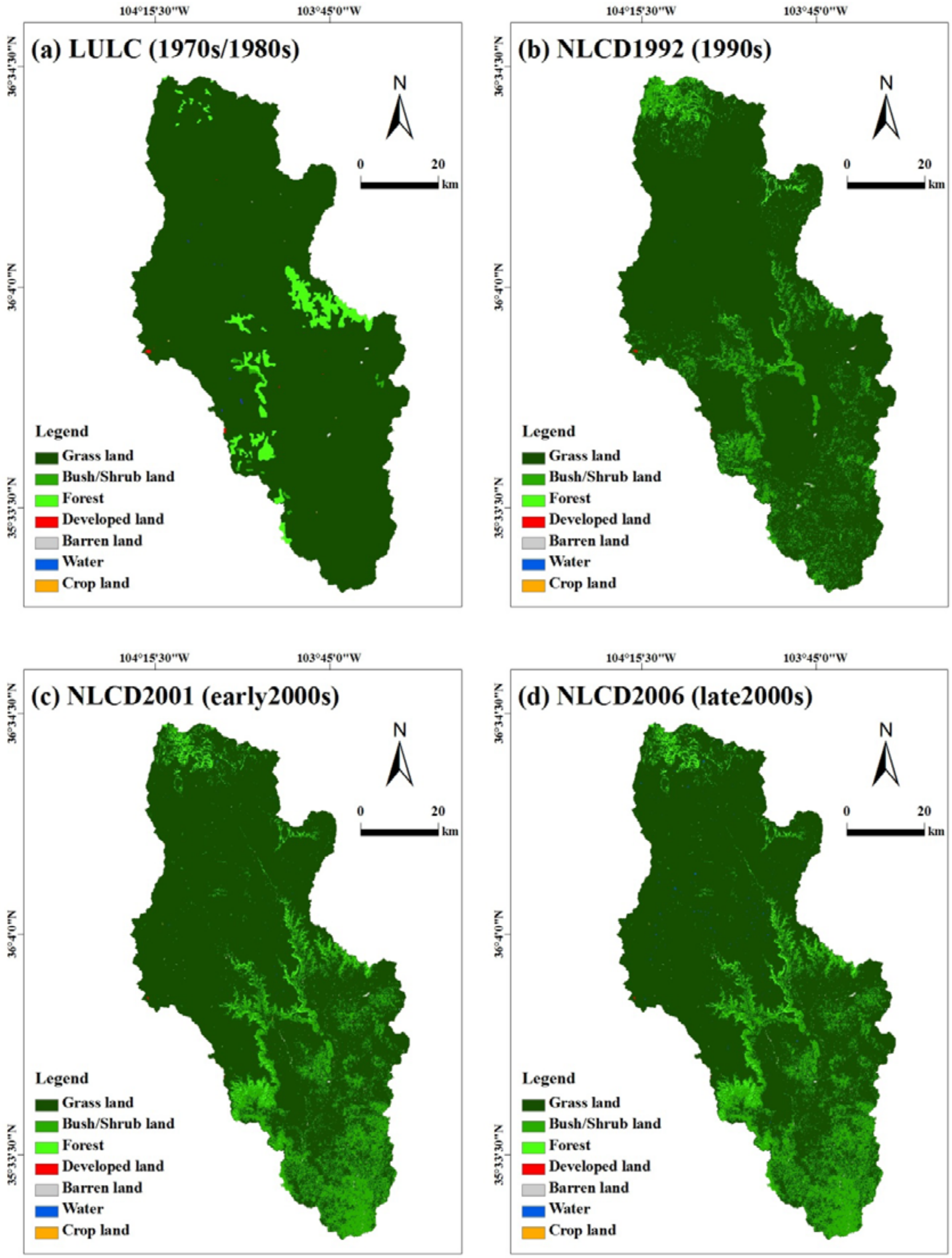

Figure 3.5. Historical land-cover maps in the study area; (a) LULC, (d) NLCD 1992, (c) NLCD 2001, and (d) NLCD 2006.

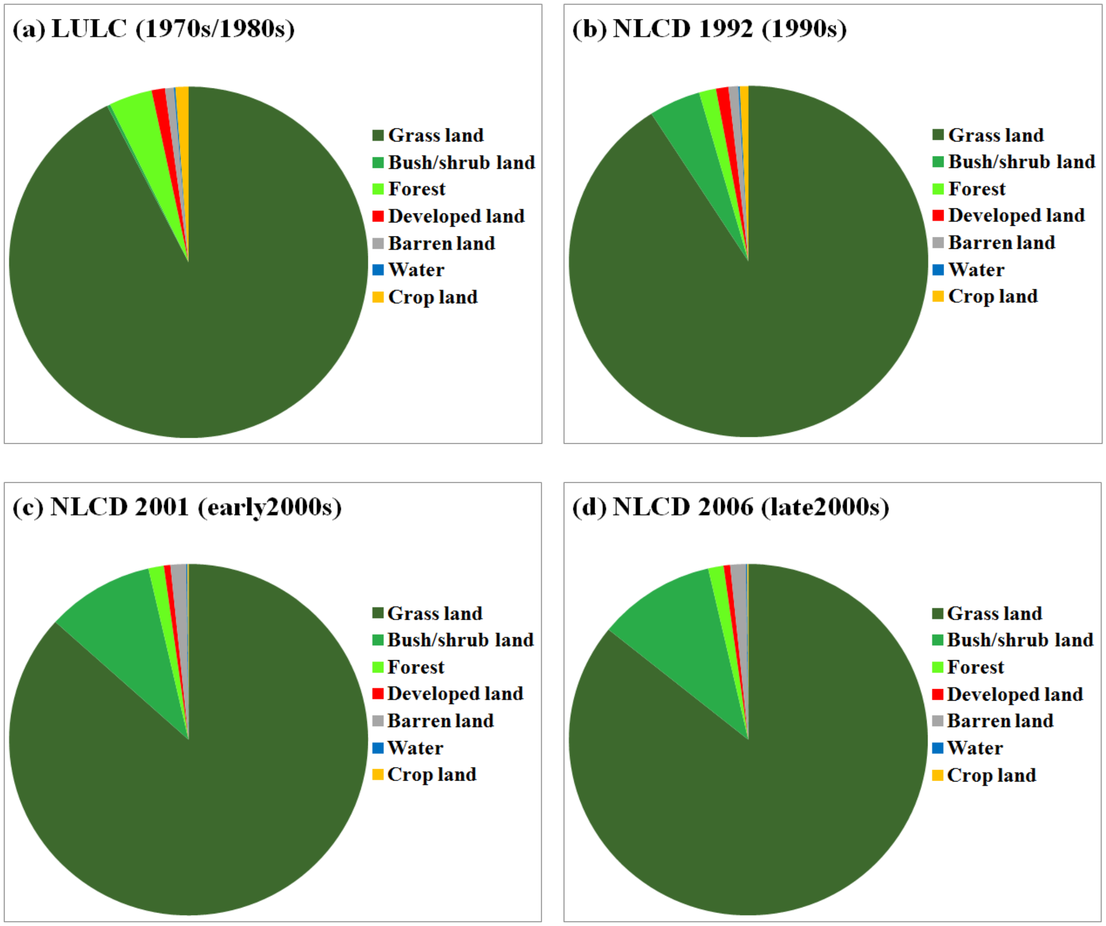

Figure 3.6. Changes of land-cover types in the study area based on the historical land-cover maps; (a) LULC, (d) NLCD 1992, (c) NLCD 2001, and (d) NLCD 2006.

Table 3.5. The area (km^2) and area percent (%) of land-cover types for each observation period based on historical-land cover data (total area= 5,289.9 km^2).

	G	BS	F	D	B	W	C	Total
LULC	4,893.7 km^2 (92.5%)	15.3 km^2 (0.3%)	205.8 km^2 (3.9%)	63.5 km^2 (1.2%)	41.8 km^2 (0.8%)	7.4 km^2 (0.1%)	62.4 km^2 (1.2%)	5,289.9 km^2 (100%)
NLCD1992	4,809.5 km^2 (90.9%)	246.0 km^2 (4.7%)	80.4 km^2 (1.5%)	59.3 km^2 (1.1%)	46.0 km^2 (0.9%)	7.4 km^2 (0.1%)	41.3 km^2 (0.8%)	5,289.9 km^2 (100%)
NLCD2001	4,585.7 km^2 (86.7%)	513.8 km^2 (9.7%)	73.5 km^2 (1.4%)	31.2 km^2 (0.6%)	74.1 km^2 (1.4%)	6.3 km^2 (0.1%)	5.3 km^2 (0.1%)	5,289.9 km^2 (100%)
NLCD2006	4,538.1 km^2 (85.8%)	561.4 km^2 (10.6%)	73.5 km^2 (1.4%)	31.2 km^2 (0.6%)	74.1 km^2 (1.4%)	6.3 km^2 (0.1%)	5.3 km^2 (0.1%)	5,289.9 km^2 (100%)
Changes	-355.6 km^2 (-6.7%)	546.1 km^2 (10.3%)	-132.3 km^2 (-2.5%)	-32.3 km^2 (-0.6%)	32.3 km^2 (0.6%)	-0.9 km^2 (0.0%)	-57.1 km^2 (-1.1%)	

G: grass land, BS: bush/shrub land, F: forest, D: developed land, B: barren land, W: water, C: crop land

Table 3.6. The comparison of land-cover change between the different time periods; (a) LULC – NLCD 1992 and (b) NLCD 1992 – NLCD 2001.

(a)		NLCD 1992							LULC
		G	BS	F	D	B	W	C	Total
LULC	G	4,788.4 km^2	105.3 km^2	-	-	-	-	-	4,893.7 km^2
	BS	-	15.3 km^2	-	-	-	-	-	15.3 km^2
	F	-	125.4 km^2	80.4 km^2	-	-	-	-	205.8 km^2
	D	-	-	-	59.3 km^2	4.2 km^2	-	-	63.5 km^2
	B	-	-	-	-	41.8 km^2	-	-	41.8 km^2
	W	-	-	-	-	-	7.4 km^2	-	7.4 km^2
	C	21.1 km^2	-	-	-	-	-	41.3 km^2	62.4 km^2
NLCD 1992 Total		4,809.5 km^2	246.0 km^2	80.4 km^2	59.3 km^2	46.0 km^2	7.4 km^2	41.3 km^2	5,289.9 km^2

G: grass land, BS: bush/shrub land, F: forest, D: developed land, B: barren land, W: water, C: crop land

Table 3.6. Continued.

(b)		NLCD 2001							NLCD 1992
		G	BS	F	D	B	W	C	Total
NLCD 1992	G	4,548.6 km^2	260.9 km^2	-	-	-	-	-	4,809.5 km^2
	BS	-	246.0 km^2	-	-	-	-	-	246.0 km^2
	F	-	6.9 km^2	73.5 km^2	-	-	-	-	80.4 km^2
	D	-	-	-	31.2 km^2	28.1 km^2	-	-	59.3 km^2
	B	-	-	-	-	46.0 km^2	-	-	46.0 km^2
	W	1.1 km^2	-	-	-	-	6.3 km^2	-	7.4 km^2
	C	36.0 km^2	-	-	-	-	-	5.3 km^2	41.3 km^2
NLCD 2001 Total		4,585.7 km^2	513.8 km^2	73.5 km^2	31.2 km^2	74.1 km^2	6.3 km^2	5.3 km^2	5,289.9 km^2

G: grass land, BS: bush/shrub land, F: forest, D: developed land, B: barren land, W: water, C: crop land

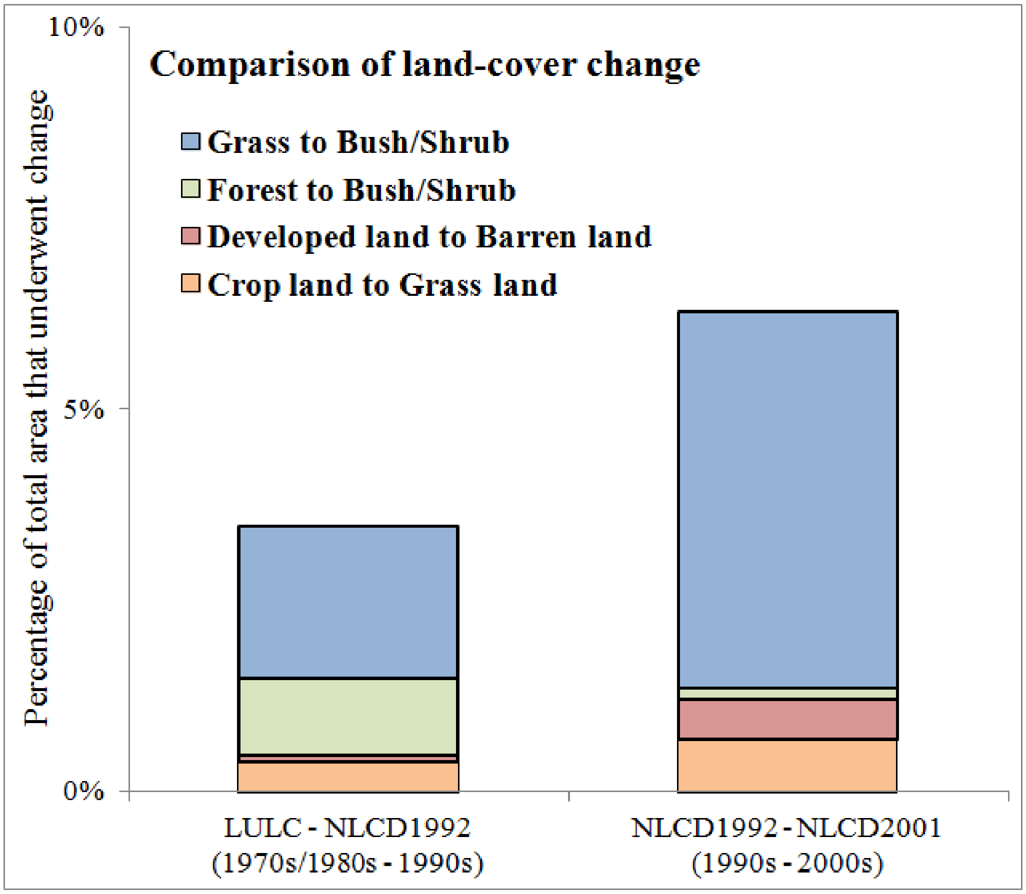

Figure 3.7. Major components of the comparison of land-cover change for the study area in LULC - NLCD 1992 and NLCD 1992 - NLCD 2001.

Changes in land cover from 1970s/1980s to 1990s

In 1970s/1980s, grass land accounted for 92.5 % (4,893.7 km^2) of the study area followed by forest (3.9 %), developed land (1.2 %), and crop land (1.2 %). Human intervention in the area is considered to be only 2.4 % (Table 3.5). During the twenty-year period from the 1970s/1980s to 1990s, significant decrease in forest and grass land covers, and an increase of bush/shrub land covers occurred. Grass land cover decreased from 4,893.7 km^2 to 4,809.5 km^2, which resulted in a change of grass land cover into bush/shrub land cover (105.3 km^2) and a gain of grass land cover (21.1 km^2) (Table 3.6 (a) and Figure 3.7 (a)). It should be noted that although the change of grass land cover to bush/shrub cover accounts for 2.2 % (105.3 km^2) of grass land cover, this change accounts for more than six times the amount of bush/shrub land cover (15.3 km^2) in 1970s/1980s. More noticeably, forest land decreased >60 % from 205.8 km^2 to 80.4 km^2. As a result of conversion of forest and grass land covers to bush/shrub land cover, the total area of bush/shrub land cover increased from 15.3 km^2 to 246.0 km^2 a 16x increase. On the other hand, evident changes in human activities occurred from the 1970s/1980s to the 1990s. In the 1970s/1980s, developed land and crop land were the third and fourth major land covers occupying 63.5 km^2 and 62.4 km^2 of the study area, respectively. In the 1990s, 6.6 % of developed land was converted to barren land cover, and ~34 % of crop land cover was converted to grass land inferring a decrease in human activities in the study area.

Changes in land cover from 1990s to 2000s

From 1990s to early 2000s, the general trend was a decrease in grass land, forest, developed land, and crop land, and an increase in bush/shrub land. Compared to the previous period, change from grass land to bush/shrub land is more significant with 260.9 km^2 (5.4 %) of grass land being converted to bush/shrub land, whereas change from forest to bush/shrub land is less significant with 6.9 km^2 (8.6 %) (Table 3.6 (b) and Figure 3.7 (b)). This increase of bush/shrub land in terms of area from 260.9 km^2 to

513.8 km^2 occurred during the ten-year period. As retreat of human activities occurred, 28.1 km^2 (47.4 %) developed land converted to barren land, and 36.0 km^2 (87.2 %) of crop land was converted to grass land, which is significantly larger compared to the previous period. Additionally, 1.1 km^2 (14.9 %) of water cover was converted to grass land. From early the 2000s to late the 2000s (Table 3.6 (c) and Figure 3.7 (c)), additional change from grass land to bush/shrub land (47.6 km^2) is occurred.

From 1970 to 2009, the study area experienced a decrease in developed land and crop land and an increase in grass land, bush/shrub land and forest. Moreover, grass land cover and forest cover decreased whereas bush/shrub land cover has increased during the last forty-year period. Based on the study of land cover conversion in Table 3.6 and Figure 3.7, the predominant trend of land-cover change was conversion of grass land and forest into bush/shrub land, and developed land and crop land into barren land and grass land in the study area. Given that the study area experienced increased temperature and decreased precipitation and the impact of human activity was minimal, one can suggested that the land-cover changes appear to be linked to changes in temperature and precipitation.

3.4.3 Change in water resources

To understand historical changes of water resources associated with changes in temperature and precipitation, simulated annual total amounts of precipitation, surface runoff, groundwater discharge, soil water content, and evapotranspiration were derived using SWAT modeling for three time-periods from 1970 to 2009, using forty years of weather data and three land-cover data sets representing each period (Figure 3.8 and Table 3.7). Study of various parameters of the study area, a semi-arid climate, suggests evapotranspiration is the major hydrologic component by far ranging from 91.7 % to 93.2 % for the three study periods (Table 3.8). Soil water content follows evapotranpiration accounting for 5.3 to 5.4 % of water storage. Surface runoff and groundwater discharge are minimal components making up less than 0.1 % of the total water. In addition, water storage was estimated based on the mass balance equation of the hydrologic cycle; water storage = input (precipitation) - outputs (surface runoff, groundwater discharge, soil water content, evapotranspiration). Figure 3.9 shows the overall proportion of each component to the total precipitation in the study area from 1970 to 2009.

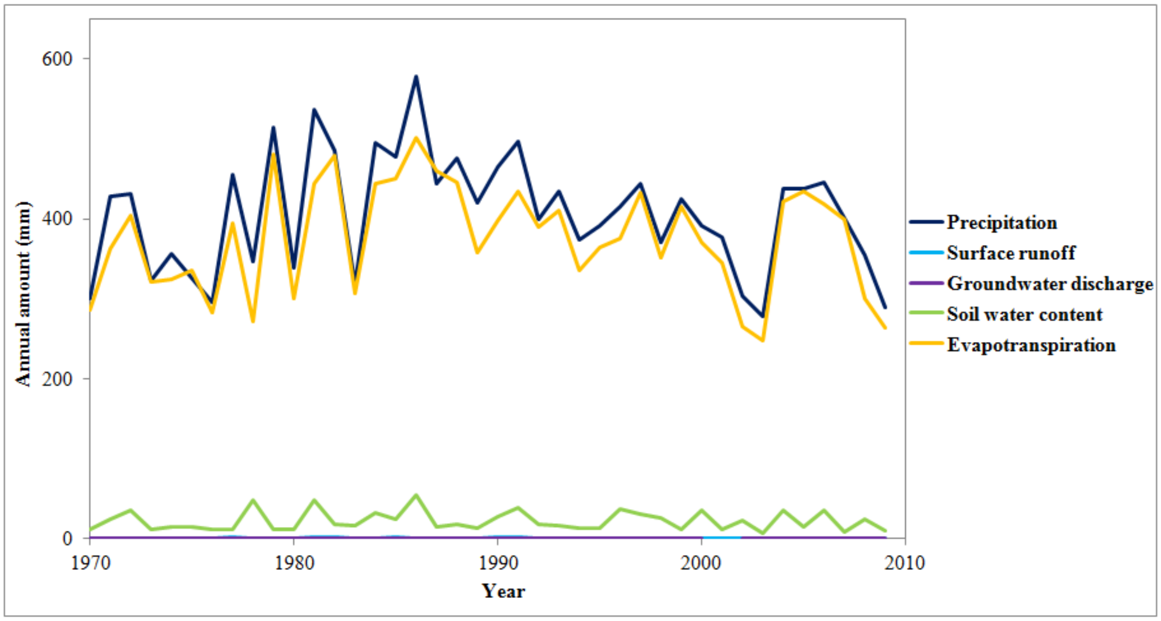

Figure 3.8. Annual total amounts in water resources derived from SWAT model for the period 1970 to 2009. The graph show: precipitation[1], surface runoff, groundwater discharge, soil water content, and evapotranspiration. The simulated precipitation is based on the observed precipitation data where periods of missing data are simulated by SWAT model.

Table 3.7. Historical annual amount of each hydrological components as derived by SWAT.

	Surface runoff mm	Groundwater discharge mm	Soil water content mm	Evapotranspiration mm
Period 1 (1970-1989)	0.381	0.050	21.926	382.323
Period 2 (1990-1999)	0.386	0.051	22.550	390.713
Period 3 (2000-2009)	0.342	0.045	20.238	346.378
Changes	-10.2 %	-10.0 %	-7.7 %	-9.4 %

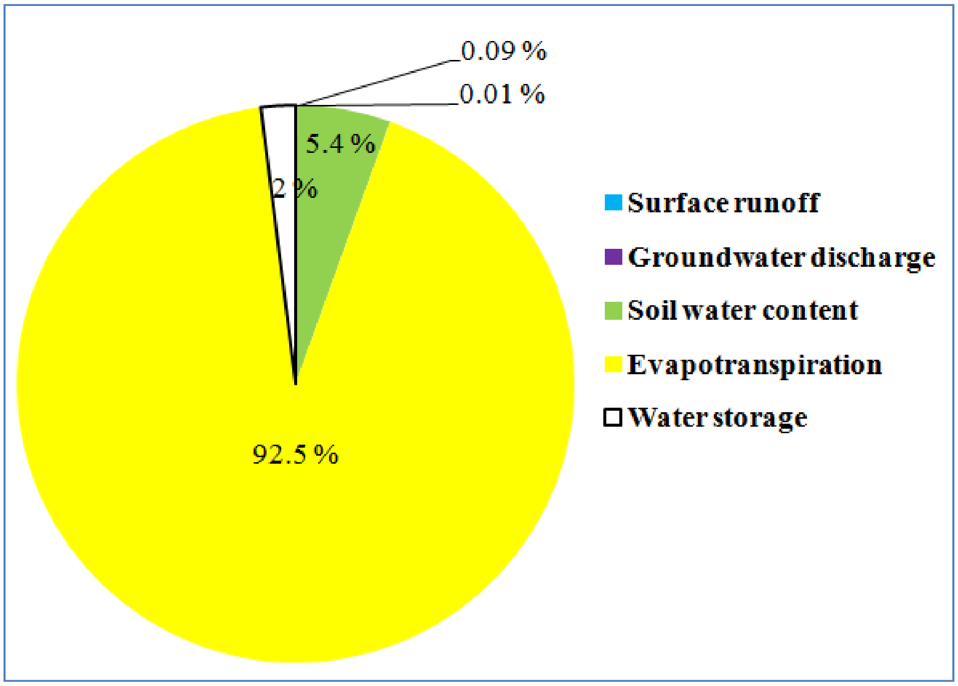

Figure 3.9. Proportion of each component of the total precipitation from 1970 to 2009. The water storage is calculated from the mass balance equation of the hydrologic cycle.

Table 3.8. Historical annual volume and the proportion of precipitation in each hydrological components as simulated by SWAT (Mton= mega ton).

	Surface runoff		Groundwater discharge		Soil water content		Evapotranspiration	
	Mton	%	Mton	%	Mton	%	Mton	%
Period 1 (1970-1989)	2.02	0.09	0.26	0.01	116	5.3	2,022	91.7
Period 2 (1990-1999)	2.04	0.09	0.27	0.01	119	5.4	2,067	92.7
Period 3 (2000-2009)	1.81	0.09	0.24	0.01	107	5.4	1,832	93.2
Overall (1970-2009)	1.96	0.09	0.26	0.01	114	5.4	1,974	92.5

Surface runoff

Annual surface runoff total ranged from 0.381 mm to 0.342 mm (Table 3.7), which accounted for 0.09 % of total annual precipitation for each of periods 1, 2, and 3 (Table 3.8). As shown in Table 3.8, the proportion to the annual precipitation total was relatively stable, and a 10.2 % decrease in surface runoff occurred during the three periods associated with a 10.9 % decrease of precipitation. From 1970 to 2009, the annual average volume of surface runoff was 1.96 mega ton and ~0.1 % of precipitation flows as surface runoff in the study area (Table 3.8). Given the climatic condition of an increasing trend in temperature and s decreasing trend in precipitation, surface runoff follows the trend of precipitation in decreasing with a relatively stable contribution in terms of the proportion of precipitation (Table 3.8).

Groundwater discharge

As the annual precipitation total decreased in the study area, annual groundwater discharge also decreased during the last forty years. Annual groundwater discharge total was 0.050 mm in period 1, 0.051 mm in period 2, and 0.045 mm in period 3 (Table 3.7). Groundwater discharge decreased by 10.0 % from 1970 to 2009 showing a decreasing trend for the study area. The annual average volume of groundwater discharge is estimated as ~0.26 mega ton, and ~0.01 % of precipitation contributes to groundwater discharge (Table 3.8). The changes in groundwater discharge appears not to play an important role in the hydrologic system of the study area, as the total amount of groundwater discharge only account for 0.01 % and the amount of change in the groundwater discharge is even smaller.

Soil water content

The annual average volume of soil water content during the study period is 114 mega ton, which suggests that 5.4 % of the averaged annual volume of precipitation is the second major hydrologic component in the basin (Table 3.8). Annual soil water content total for period 1, 2, and 3 is 21.926 mm, 22.550 mm, and 20.238 mm, which decreased by 7.7 % (Table 3.7). The annual precipitation total decreased by 10.9 % during the same periods. The proportion of soil water content to the annual precipitation total, however, slightly increased from 5.3 % in period 1 to 5.4 % in period 3. Given a 10.9 % decrease in precipitation associated with a 0.9 ˚C increase of temperature, the changes in soil water content appears to follows the same trend of precipitation (Figure 3.8).

Evapotranspiration

Evapotranspiration of 382.323 mm occurred in period 1; 390.713 mm in period 2; and 346.378 mm in period 3. A decreasing trend from period 1 to period 3 can be seen (Table 3.7). At the time precipitation decreased by 10.9 %, evapotranspiration decreased by 9.4 % during the last forty year, which is a relatively lower rate of decrease than that for precipitation. The annual average volume of evapotranspiration was 1,974 mega ton, which accounted for 92.5 % of the precipitation received (Table 3.8). One can infer that evapotranspiration is the most important hydrologic parameter in a semi-arid climate watershed.

As the study area experienced an increase in temperature and a decrease in precipitation, the evapotranspiration rate decreased during the observation period. Although temperature is considered to be a major factor controlling evapotranspiration whereas increasing temperature would should result in an increase in evapotranspiration, evepotranspiration in the study area tracks precipitation trend.

3.5 Discussion

The impact of changes in temperature and precipitation on water resources were investigated for a semi-arid watershed from 1970 to 2009. The watershed is located in New Mexico, USA. To define impact of change in climate, a sub-basin with minimal human development was chosen. The changes in temperature and precipitation from 1970 to 2009 were analyzed. Land-cover changes estimating from 1970s to the 2000s was also analyzed. Moreover, water resources were simulated with a SWAT model over a forty-year time period. The simulation was based on the weather data and the land-cover data representing different periods of time for the study area.

3.5.1 Changes in temperature and precipitation

From 1970 to 2009, a 0.9 °C increase in temperature from 11.0 °C to 11.9 °C occurred and ~11 % decrease from 406.7 mm to 362.2 mm in precipitation occurred (Table 3.4). Numerous links have been suggested between various parameters affecting temperature change. The parameters suggested are CO_2, air pollution, green house gases, and land-cover changes (Neff et al. 2000; Wang et al., 2008; Li et al., 2009; USGCRP, 2009). Also, previous studies for arid or semi-arid climate have confirmed that temperature is increased by increased CO_2, air pollution, and expanded human population and development (IPCC, 2007; Bao and Fang, 2009; Li et al., 2009; Praskievicz and Chang, 2009; Wang et al., 2011).

Local temperature variations can be enhanced by land-cover change brought about by human impacts. Developed land has a relatively high heat capacity and albedo, which can contribute to temperature increases (McMahon et al., 2003; Claessens et al., 2006). Additionally, USGCRP (2009) demonstrated that global temperature can increase as a result of human impacts. They also demonstrated that global temperature can be slowly increased without human impacts; this was demonstrated using the GCM model.

This present study is focused on the changes in temperature and precipitation in a semi-arid watershed that has minimal human impact, which might cause change in local temperature in addition to the increase in global temperatures. For a semi-arid watershed with 1 % or less developed land, temperature increased 0.9 °C. As in previous studies (Chapter 3.4.1) arid or semi-arid climate reported temperature increase of 1.5 to 2.5 °C with a considerable amount of developed lands, the present study reveals a lower magnitude in the increase in temperature. The present study has minimal human development, which is a major reason for the small temperature increase when compared to previous studies. Thus, this study infers variations of temperature caused primarily by a change in the climate resulting from natural condition.

Precipitation patterns are governed primarily by the availability of moisture, land cover, and atmospheric circulation patterns (USGCRP, 2009). Human activities also influence precipitation pattern at the global scale by producing air pollutants and aerosols which affect changes in atmospheric transmission which in turn affects solar radiation and air circulation (ICPP, 2007). At a local scale, land cover plays an important role in affecting precipitation. It is reported that human activity has produced a decrease in precipitation because developed lands decrease soil infiltration and can reduced evaporation rates (Stefanov et al., 2001; Ragab and Prudhomme, 2002; Bao and Fang 2009; Favreau et al., 2009; Dixon and Earls, 2012).

Vegetation also affects precipitation. Leaf cover directly impacts transpiration rates, and roots of plants store water, which provide stored water to increase evaporation rates and subsequently increase precipitation in general (Eagleson, 1978; Kim and Wang, 2007). Vegetation impact on precipitation patterns varies depending on the type of vegetation and its extent (IPCC, 2007; Peel et al., 2010; Tsegaye et al., 2010; Brummer et al., 2012). For example, cactus, the dominant shrub vegetation in arid environment, is designed to conserve water and not to transpire water from vegetation whereas broad-leaf trees, the main vegetation in humid regions, do not need to conserve water. Thus, they transpires water into the atmosphere (Bachelet et al., 2001; Kim and Wang, 2007).

In the study area, precipitation decreased from ~407 mm to ~362 mm during the forty- year study period, which account for an ~11 % decrease (Table 3.4). Given that the land cover is mainly grass land cover and bush/shurb land cover (~93 %), the effect of developed land on precipitation is minimal. Based on the general relationship between land cover and precipitation, the current study has not established a significant change in precipitation. This suggests that grass land cover and bush/shrub land cover in the study area appear not to contribute to local precipitation. As global precipitation patterns for an arid or semi-arid climate shows a decreasing pattern of 5 to 10 % (IPCC, 2007; USGCRP, 2009; Arnell et al., 2011), the climate of the study area follows the global trend of decreasing precipitation. In addition, human impact is minimal and the precipitation trend follows the global trend of a decrease in precipitation.

3.5.2 Changes in land cover

As an interconnected system, climate, hydrology, land cover are linked to local temperature and precipitation. Changes in land cover are linked to changes in climate and/or human use. On the short-term basis (< thirty years) a major factor in causing land-cover change is human activities. From 1970 to 2009, grass land has been the major land cover in the study area ranging from 85.8 % to 92.5 % (Table 3.5). In 1970s, forest (3.9 %), developed land (1.2 %), and crop land (1.2 %) occupied a small share of the land cover. By the 2000s, slight changes occurred with bush/shrub land (10.6 %), forest (1.4 %), and barren land (1.4 %). Two major trends of land-cover changes in the study area occurred over the forty-year observation based on the spatial analysis of land cover conversion; a significant amount of conversion from grass land and forest to bush/shrub land, and a change of developed land and crop land to barren land and grass land, respectively (Table 3.6 and Figure 3.7). During the study period, 413.8 km^2 (= 105.3 + 260.9 + 47.6) of grass land and 132.3 km^2 (= 125.4 + 6.9) of forest changed to bush/shrub land accounting for 8.5 % and 64.3 % of grass land and forest land, respectively. If both land-cover changes are combined, 10.3 % of the total study area experienced changed to bush/shrub land, which is greater than the area of the other four land covers combined (Table 3.5).

In general, climate does have an influence on the type of vegetation and the distribution and density. Some types of vegetation are influenced much by temperature whereas other types of vegetation are influenced by precipitation (Lenihan et al., 2003; Peel et al., 2010). It is known that grass land is the dominant vegetation in regions where annual total precipitation is <500 mm whereas shrub and bush land, including cactus, are major vegetation types found in arid environments (Neilson, 1995; Kim and Wang, 2007; Brummer et al., 2012). Tsegaye et al. (2010) mentioned that the Northern Ethiopia, consisting of grass, bush, forest, developed land, and crop land, experienced a decrease in grass and forest by ~7 % and ~8 %, respectively and an increase in bush cover by ~11 % during a 35-year period from 1972 to 2007. They also mentioned that crop land increased by 0.02 % as the population increased from ~27,000 in 1996 to ~38,000 in 2007. They concluded that changes in the type of vegetation were mainly caused by the increasing occurrence of drought, natural succession (bush/scrub land was replaced when crop production was abandoned, bare land turned into grass land and bush/scrub land when left untouched), and use as firewood associated with the population growth.

Tefera (2011) studied Central Ethiopia, including 99 % of rural area in the area. He showed a decrease in grass land and forest land by ~21 % and 21.5 %, respectively, and an increase in shrub land by 10 %. He concluded that changes in the type of vegetation were induced by drought, precipitation variability, and population movement. Moreover, drought and forest fires cause conversion of forest to shrub and bush land (Shiferaw, 2011).

Some studies suggested that forest land cover will be decreased, but bush land cover will be increased because of increased CO_2 and resulting climate change. Climate change is influencing vegetation types through changes in length of daytime, heat index, seasonal variation, and maximum temperatures (Bachelet et al., 2001; Domingo et al., 2001).

The study area experienced a decrease in precipitation from 406 mm to 362 mm and an increase in temperature from 11.0 °C to 11.9 °C, it appears that the climate of the study area is gradually moving towards an arid environment from semi-arid environment. The patterns of change in temperature and precipitation are the main causes of land-cover changes from grass land and forest to bush/shrub land, based on the spatial analysis of land-cover conversion (Table 3.6 and Figure 3.7).

On the other hand, 32.3 km^2 (= 4.2 + 28.1) of developed land was abandoned to revert to barren land, and 57.1 km^2 (= 21.1 + 36.0) of crop land was converted into grass land accounting for 91.5 % of crop land cover in the study area during the forty-year observation (Table 3.6). Developed-land cover and crop-land cover are mainly considered as types of land covers related to human activities. Human activities, such as agriculture, settlement, road construction, commercial development and policies, are important factors directly affecting land-cover changes. Generally, human intervention has more effect on land-cover change than climate change because the effects of climate change take a long period of time to impact land-cover changes (Li and Yeh, 2004). Decreasing patterns of land cover related to human activities can be considered an indication of decline in human activities including residential, commercial and agricultural.

It has been suggested that climate change has influenced the decreases in crop production and agricultural species, which may lead to an indirect cause of population decline (Tingem et al, 2008). Additionally, with decreasing precipitation and increasing temperature occurring water availability for municipal and agricultural use has been reduced. The study area has experienced declines in the groundwater level since 1970s. In addition, the population has decreased from 1,348 in 1970 to 678 in 2009 (Harding County, NM; US Census Bureau, 2010). As climate progresses towards a more arid climate, a harsher environment for crop production and increased deficit in available water for human activities has occurred. These changes suggest that land-cover changes appear to be related to decreasing human activities in the study area. (Table 3.6 and Figure 3.7).

3.5.3 Changes in water resources

A hydrologic system consists of precipitation, surface runoff, groundwater discharge, soil water, evapotranspiration and water storage. The hydrologic system of the study area consists of 92.5 % evapotranspiration, 5.4 % soil water, 0.09 % surface runoff, and 0.01 % groundwater discharge (Table 3.8). Water storage is estimated to be 2.0 % of the total precipitation received based on the mass balance equation (Figure 3.9).

Previous research has suggested that a high portion of precipitation is lost through evapotranspiration in arid regions (Sun, 2004; Joh et al., 2011; Brummer et al., 2012). Domingo et al. (2001) reported that 96 % of the precipitation was lost as evapotranspiration and 1 % of the precipitation became surface runoff in a typical semi-arid watershed in southeastern Spain. Dahm et al. (2002) suggested that evapotranspiration and surface runoff account for 93 % and 2 % losses in a semi-arid watershed located in New Mexico. This watershed had land covers consisting of barren land, vegetation, and cropland. In another study focused on a semi-arid watershed in western US from 1957 to 1998, Golubev et al. (2001) suggested that precipitation was estimated to be 91 % of the precipitation was lost through evapotranspiration, 5 % through surface runoff. All their calculation were based on a hydrological balance model. Compared to previous studies (Domingo et al., 2001; Golubev et al., 2001; Dahm et al., 2002; Brummer et al., 2012), their calculated rate of evapotranspiration is similar whereas the runoff rate is significantly lower than the other basins. The deficit in runoff is thought to be compensated for by relatively higher rates of soil water by 5.4 %. This difference is mainly caused by the types of land cover whereas previous studies included considerable amounts of developed lands, which hindered infiltration and increased surface runoff. The proportional higher rate of soil water is more likely to occur in a semi-arid basin with minimal developed land.

Local temperature, precipitation and land cover directly affect the local hydrologic system. Local climate may be influenced by more regional geography outside of the local basin system, such as global climate change, ocean water currents, and air circulation patterns (Kuchment, 2004; USGCRP, 2009). The study area is characterized by a ~1 °C increase in temperature and ~11 % decrease in precipitation, and a land-cover change of grass and forest conversion to bush/shrub land, and a decrease in human activities. The climate and land-cover changes resulted in a 10.2 % decrease in surface runoff, a 10.0 % decrease in groundwater discharge, a 7.7 % decrease in soil water content, and a 9.4 % decrease in evapotranspiration from 1970 to 2009 (Table 3.7).

Surface runoff

Surface runoff is defined as the flow of water over the surface of land following a precipitation event, it is the water that is not evaporated, stored as soil water, or infiltrated to a aquifer but flows to a stream channel (IPCC, 2007; SWAT 2009 input/output file documentation). Generally, surface runoff has a similar trend to that of precipitation (Guo et al., 2008; Lespinas et al., 2010). On the other hand, if changes in land cover are affected by human activities including land already developed, the surface runoff will shows a relatively higher increase in change than the increase in change for precipitation because developed land causes a decrease in infiltration and increases velocity and the volume of surface runoff (Claessns et al., 2006; Kucukmehmetoglu and Geymen, 2008; Dixon and Earls, 2012).

The main factor causing the change is the increase in impervious surface area. From 1970 to 2009, developed land in the study area decreased from 63.5 km^2 to 31.2 km^2 (Table 3.5), which had minimal impact on the hydrologic system. The 10.2 % decrease in surface runoff follows the similar decreasing pattern in precipitation (Table

3.7). Thus, it is assumed that surface runoff in the study area can be linked to decrease in precipitation.

Gourndwater discharge

Groundwater discharge contributes to streamflow and is an indicator of groundwater movement from an aquifer to a main stream (SWAT 2009 input/output file documentation). Generally, it is assumed that high precipitation regions are assumed to experience an increase in groundwater discharge, whereas low precipitation regions are assumed to experience a decrease in groundwater discharge (IPCC 2007; Ma et al., 2009). For example, a low amount of precipitation results in a decreases in surface runoff and the groundwater recharge rate, which eventually leads to a decrease in groundwater discharge (Eckhardt and Ulbrich, 2003; He et al., 2009).

The current study showed that groundwater discharge decreased by 10.0 % (Table 3.7), whereas precipitation decreased by ~11 % from 1970 to 2009. Researcher suggested that human intervention also directly affected the groundwater discharge (Gleick et al., 1987; USGCRP, 2009; Weider and Boutt, 2010). Gleick et al. (1987) reported that Sacramento basin in US has experienced a 15% decrease in groundwater discharge since 1970s because of population growth. They concluded that human intervention has more influence than climate change on short-term change in groundwater discharge because groundwater slowly responds to climate change.

The land-cover change in the study area saw developed land and crop land decreasing to 0.6 % and 0.1 % of the total area, respectively (Table 3.5). The developed land and crop land in the study area account for a very small proportion, which may not affect groundwater use. Although groundwater use in the study area can be basically ignored for human activities as the result of decreasing human presence, the study area, nevertheless, has experienced decline in groundwater levels since 1970s (USGS Groundwater Resource, 2009B). This fact suggested that groundwater discharge in the study is affected by climate, rather than human use including irrigation and municipal uses. Thus, one can assume that a semi-arid watershed experiencing a decrease in precipitation may continuously see a continual reduction in groundwater recharge.

Soil water content

Soil water content is defined as the amount of water in the soil profile. This parameter shows the available water capacity, which can be stored in the soil (IPCC, 2007; SWAT 2009 input/output file documentation). Soil water content is affected by temperature and precipitation (Gleick, 1987; Giambelluca, 2005; Joh et al., 2011). In general, high temperature leads to an increase in the rate of evapotranspiration, which can result in a decrease in soil water content whereas high precipitation can directly result in an increase in soil water content (Giambelluca, 2005; USGCRP, 2009). Previous studies suggest that soil water content can also be influenced by land cover (Fontaine et al, 2001; Hamdi et al., 2011; Zhou et al., 2011).

Zhou et al. (2011) concluded that soil water content decreased by only 5 % in semi-arid watershed of Southern China over the last 25 years even through the area experienced a 10 % decrease in precipitation, which was offset by land cover. Previous studies suggested that an increase in vegetation cover and a decrease in developed land cover can have a positive impact on soil water content (Foraine et al., 2001; McMahon et al., 2003; Zhou et al., 2011).

The study area showed a 7.7 % decrease in soil water content from 1970 to 2009 as precipitation decreased 10.9 % (Table 3.7). During the forty years of observation, total vegetation (sum of grass, bush/shrub, and forest) increased by 1.1 %, which accounted for 97.8 % of the total area. Developed land decreased by 0.6 %, which accounted also for 0.6 % of the total area (Table 3.5). The ~11 % decrease in precipitation was offset by a high proportion of vegetated area. In addition, developed land decreased, which contributed to a minimal decrease in soil water content.

Evapotranspiration

Evapotranspiration is defined here as the combined evaporation from the surface of Earth and transpiration of plants, which represent the total loss of water from the surface to the atmosphere (SWAT 2009 input/output file documentation). It is assumed that the rate of evapotranspiration is increased by high temperatures, wind speed and albedo. On the other hand, evapotranspiration can be reduced by high humidity (Ziegler et al., 2005; Joh et al., 2011; Brummer et al., 2012). Historical rates of evapotranspiration are difficult in obtain. The difficulty was in obtaining the various factors, such as wind speed, solar radiation, albedo and humidity because of lack of technical instruments and measurement errors.

Given the historical observation for temperature and precipitation in the study area, the analysis may include uncertainty in the rate of evapotranspiration reported. Moreover, the pattern of evapotranspiration is complicated as it varies depending on different environments. In arid environments, like the study area, evapotranspiration is directly influenced by precipitation because arid regions have low humidity and low rates of precipitation (Dahm et al., 2002; IPCC, 2007; USGCRP, 2009; Peel et al., 2010). In addition, evapotranspiration is also affected by land cover. In general, greater vegetation cover increases evapotranspiration, whereas areas that have a large percentage of developed land cover causes a decrease in rate of evapotranspiration (Clasessens et al., 2006; Ma et al., 2009; Peel et al., 2010). The study area has experienced a decrease in the rate of evapotranspirations by 9.4 % from 1970 to 2009 (Table 3.7). During the same period time, the study area experienced a 0.9 °C increase in temperature and ~11 % decrease in precipitation.

Previous studies report that, in semi-arid environments, the rate of evapotranspiration to precipitation received ranges from 87 to 93 %, which are relatively lower than arid environments (Domingo et al., 2001; Muttiah and Wurbs 2002; Sun, 2004; USGCRP, 2009). In the study area, land-cover changes, during the period of observation, showed a decrease of grass and forest and significant increase of bush/shrub land. Overall the total vegetation (sum of grass, bush/shrub, and forest) increased from only slightly 96.7 % to 97.8 %. Because grass and forest covers contribute more to the rate of evapotranspiration than bush/shrub land, the rate of evapotranspiration in the study area does not follow the normal relationship of a decrease in precipitation. Other factors, such as wind speed, solar radiation, albedo and humidity, also must be considered to understand the response of the rate of evapotranspiration clearly.

3.6 Conclusions

The impact of changes in temperature and precipitation on water resources in a watershed with a semi-arid watershed from 1970 to 2009 have been investigated. A watershed with minimal human impact was chosen to evaluate the natural response of water resources to changes in temperature and precipitation. Historical land cover data for three different periods representing 1970s/1980s, 1990s and 2000s, respectively, were used. A SWAT model was used to model the characteristics and variations of water resources components for the three periods.

During the forty years of observation, the temperature increased by ~1 °C with an increasing trend. Although previous studies of other location around the world have different observation periods, the current study has less increase in temperature than the other studies. During the same time period, precipitation decreased by ~11 % which is similar to the other studies. As temperature increased and precipitation decreased during the last forty years, changes in land cover decreased in grass land (~93 % to ~86 %), forest (~4 % to 1.4 %), developed land (1.2 % to 0.6 %), and crop land (1.2 % to 0.1 %), and increased in bush/shrub land (0.3 % to ~11 %), and barren land (0.8 % to 1.4 %) (Table 3.5).

The predominant changes of land covers were conversions of developed land and crop land to barren land and grass land, and a significant amount of conversion from grass land and forest to bush/shrub land, respectively (Table 3.6 and Figure 3.7). These changes suggest that conversion of developed land and crop land into barren land was influenced by a decrease in population from 1,348 in 1970 to 678 in 2009 during the study period (US Census Bureau, 2010). It further suggests that changes in temperature and precipitation affected land-cover changes including types of vegetation where human intervention is minimal. One can suggest that climate has a slower impact on land-cover change.

The impact of changes in the various parameters on water resources for a semi-arid climate watershed were examined, based on observation data and SWAT simulations for the period 1970 to 2009. Evaluation of the distribution of precipitation shows 92.5 % became evapotranspiration, 0.09 % became surface runoff, 0.01 % contributed to groundwater discharge, and 5.4 % was stored as soil water content (Table 3.8). Evaluation of water storage in the study area suggested that 2.0 % of the precipitation served as a positive contribution based on the mass balance equation of the hydrologic cycle (Figure 3.9). Compared to other previous studies of other areas, the study area basin has a similar rate of evapotranspiration, but surface runoff is lower than other arid or semi-arid areas.

Changes in temperature and precipitation can be summarized by a 0.9 °C increase in temperature and an ~11 % decrease in precipitation, and conversion of grass and forest into bush/shrub land and a decrease in human activities. Analysis of the data suggests a 10.2 % decrease in surface runoff, a 10.0 % decrease in groundwater discharge, a 7.7 % decrease in soil water content, and a 9.4 % decrease in evapotranspiration from 1970 to 2009 (Table 3.7). It is assumed that these changes are linked the changes in climate and changes in land covers. Thus, one can conclude that surface runoff and groundwater discharge generally follow a similar trend in precipitation in the study area; this occurs with the minimal human impact. Changes in the volume of soil water content is relatively offset by the trends of precipitation and land-cover changes. Evapotranspiration rates in the study area have a relatively similar rate in other studies of semi-arid climates. Finally, vegetation appears not to have a significant effect on evapotranspiration in arid or semi-arid environments.

4. GENERAL CONCLUSIONS

This dissertation investigated the responses of water resources to changes in temperature and precipitation in two watersheds with different climates. As an interconnected system of climate, land cover, and water resources, the research explains the relationship between water resources and the impact that the changes in temperature, precipitation, land covers in the two different watersheds from 1970 to 2009 based on historical data and SWAT simulations. The results contribute to understanding the impact of changes in temperature and precipitation on water resources in a humid watershed and a semi-arid watershed. It provides the knowledge necessary for water resources management to make informed decisions.

The first study (Chapter 2) evaluated the impact of changes in temperature and precipitation on water resources in a watershed with a humid subtropical climate from 1970 to 2009. The study area had minimal human impact and forty years of data were used. The study determined changed in land cover changes by comparing three land cover data sets for the forty years of observation, representing three periods; 1970s/1980s, 1990s, and 2000s. To provide a realistic picture, three SWAT models were constructed for the three periods (period 1: 1970-1989, period 2: 1990-1999, period 3: 2000-2009) using different land cover data (period 1: LULC, period 2: NLCD 1992, period 3: NLCD 2001).

A 0.7 ℃ increase in temperature occurred during the forty years of observation, and the magnitude of temperature variation was lower than previous studies that dealt with other humid climate watersheds. On the other hand, precipitation increased by ~16 % during the same period, and the rate of increase was higher than previous studies on other areas. Temperature had a relatively stable increase and precipitation showed a high rate of increase, land cover changed through increases of bush/shrub (0.2 % to 9.1 %), developed land (1.1 % to 6.3 %) and crop land (3.1 % to 3.5 %), and decreases of grass (0.7 % to 0.1%), forest (94.0 % to 80.6 %) and barren land (0.7 % to 0.1 %) from 1970 to 2009. The major trend of land cover change was conversion of forest, grass, and barren land into developed land and crop land via human activities, and forest and grass into bush/shrub by changes in the natural system (Table 2.6 and Figure 2.7). This study demonstrated that human activities were the major contributors in land cover change from 1970 to 2009.

As an interconnected system of climate, land cover, and water resources, this study analyzed the water resources components for a humid subtropical watershed based on forty years of observation data and SWAT simulations. The analysis showed that evapotranspiration was ~52 %, surface runoff was 16.3 %, groundwater discharge was 0.9 %, soil water content was 19.3 %, and water storage in this humid subtropical watershed was 11.6 % (Table 2.8). In addition, the analysis showed a slightly higher evapotranspiration rate and a markedly lower surface runoff rate compared to other humid climate studies because of vegetation dominance in the land cover. This dissertation also investigated the hydrologic response to climate and land cover changes during the forty years of observation. As precipitation increased by 16.3 % and land cover changed by 30 %, surface runoff increased by 15.0 %, groundwater discharge decreased by 9.2 %, soil water content increased by 2.7 %, evapotranspiration increased by 20.1 % (Table 2.7). All this leads one to suggest that concluded that surface runoff was relatively stable with precipitation, whereas groundwater discharge and soil water content were sensitive to land cover changes especially these changes occurring as the result of human intervention. One can also concluded that land cover played an important role in evapotranspiration.

The second study (Chapter 3) investigated the effect of changes in temperature and precipitation on water resources in a semi-arid watershed from 1970 to 2009. This study analyzed the impact of changes in climate on water resources in a study area with minimal human influence. Land cover data for three different time periods representing 1970s/1980s, 1990s, and 2000s, respectively, were developed using historical satellite data. Land cover changes were studied using ArcGIS® spatial analyst module for a forty-years period. The study simulated the changes in water resources using three SWAT simulations from 1970 to 2009, based on the weather and land cover data representing three different periods (period 1: LULC and weather data from 1970 to 1989, period 2: NLCD 1992 and weather data from 1990 to 1999, period 3: NLCD 2001 and weather data from 2000 to 2009).

This study found a 0.9 °C increase in temperature and a ~11 % decrease in precipitation from 1970 to 2009. The trend in temperature increased with a obvious decreasing trend in precipitation. Although previous studies of different locations used different observation periods, the current study showed a lower increase of temperature but a similar decrease in rate of precipitation.

In the study area, a temperature increased and precipitation decreased during the last 40 years, numerous land cover changes occurred. For example, grass land decreases from 92.5 % to 85.8 %, forest cover decreased from 3.9 % to 1.4 %, developed land decreased from 1.2 % to 0.6 % and crop land decreased from 1.2 % to 0.1 %. However, bush/shrub land cover increased from 0.3 % to 10.6 % and barren land increased from 0.8 % to 1.4 %. The predominant trend in land cover changes was conversion of developed land and crop land into barren land and grass land, and grass land and forest into bush/shrub land (Table 3.6 and Figure 3.7). The decrease of developed land and crop land is associated with a decreasing population in the study area from 1,348 in 1970 to 678 in 20009 (US Census Bureau, 2010) during the forty-years period. However, the decrease in grass land and increase in bush/shrub land is considered to be the result of changes in natural process. It is suggested that a 0.9 °C increase in temperature and a ~11 % decrease in precipitation may be sufficient to affect land cover changes including types of vegetation although land cover change has a slower response to long-term climate change.

The effect of various parameter of hydrologic cycle on water resources for a semi-arid watershed, based on observation data and SWAT simulations from 1970 to 2009, were undertaken. The results suggest that precipitation contributions to the hydrologic parameters in a semi-arid watershed were 92.5 % lost to evapotranspiration, 0.09 % lost as surface runoff, 0.01 % lost to groundwater discharge, 5.4 % was stored as soil water content, and 2.0 % was water stored (Table 3.8). Compared to other studies of other locations, the current study showed a similar rate of evapotranspiration, but the surface runoff rate was lower than other arid or semi-arid areas. In response to climate and land cover changes, surface runoff, groundwater discharge, soil water content, and evapotranspiration decreased by 10.2 %, 10.0 %, 7.7 %, and 9.4 %, respectively, during the forty-years of observation (Table 3.7). It is suggested that the various hydrologic parameters showed generally similar patterns to that of precipitation for an arid or semi-arid climate, and the volume of soil water was relatively offset by general trend of precipitation with land cover. Evapotranspiration in the study area showed a similar rate to the rates presented for other semi-arid climate watersheds. It appears that vegetation did not play a meaningful role in affecting evapotranspiration in the study area.

This dissertation evaluated the impact of changes in temperature and precipitation on water resources in two watersheds with different climates; a humid-subtropical climate and a semi-arid climate. The humid-subtropical climate watershed experienced increasing trends in temperature and precipitation. It is suggested that developed land and crop land increases were the result of increase in the human population of the area, whereas grass and forest decreases and bush/shrub increases were the result of natural process.

Water resources generally showed the similar increasing patterns of precipitation for a humid-subtropical climate watersheds with minimal human activity. Groundwater discharge and soil-water content were relatively sensitive to changes in land cover caused by human intervention. On the other hand, the semi-arid climate watershed had an increase in temperature and a decrease in precipitation. Human intervention was minimal, which can be associated with the low magnitude of change in temperature and a similar decrease trend in precipitation.

Land cover change was characterized by conversion of developed and crop land cover into barren land and grass land cover. This change is thought to be the result of the decrease in human activities. Changes in grass and forest cover into bush/shrub cover is suggested to be associated with natural process.

The trend in water resources generally followed the similar decreasing trends of precipitation for a semi-arid watershed with minimal human impact. The volume of soil water was relatively offset by climate and land cover changes.

Overall, the present study showed a low magnitude of change in temperature and a similar low magnitude of change in precipitation because the study area has minimal human activities. Because human impacts in the study area have been minimal, one can suggest that changing global conditions are playing an important role in impacting the changes in the study. When human impacts were minimal, the changes in temperature and precipitation might have associated with the natural climate system or global climate (USGCRP, 2009; Cuo et al., 2011). Human activities affected the changes in land covers of developed land and crop land, and natural processes influenced the rates of conversions of grass and forest into bush/shrub in the two climate-zone watersheds. The humid-subtropical climate displayed conversion of grass, forest, and barren land into developed and crop lands as the result of increased population impact. The semi-arid climate watershed showed a conversion in developed and crop lands as a result of a decrease in human activities. It can be suggested that changes in temperature and precipitation may be sufficient enough to be responsible to cause the conversion of grass and bush/shrub cover to forest cover in the two climate-zone watersheds.

The pattern in water resources followed a similar patterns of precipitation for the two climate-zone watersheds. In the humid-subtropical climate watershed, an increase trend in precipitation occurred whereas groundwater discharge and soil-water content were sensitive to changes in land cover caused by human activities. In the semi-arid climate, a decreasing trend in precipitation occurred, and the volume of soil water was relatively offset by precipitation and land cover changes.

This research contributes on understanding of the responses of water resources associated with changes in temperature and precipitation in the two different types of climates. Thus, this research can provide important information for water resources manager in making important decision and developing plans for use of the water resources in the future for; a humid-subtropical climate watershed and a semi-arid climate watershed.

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